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The effects of swimbladder size, condition and gonads on the acoustic target strength of mature capelin

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Pre- and post-spawning capelin from the Barents Sea stock were observed in a net pen with a calibrated 38 kHz scientific split-beam echosounder. The transducer was positioned vertically or tilted. The acoustic target strength (TS) of capelin depended on swimbladder length. In female capelin within 15.5–18.0 cm length the logarithm of weight was significantly negatively related to TS. The negative effect of weight on TS could be due to a higher condition factor (assumed higher fat content), which gave the fish additional buoyancy and less need for swimbladder volume. The effect of gonad weight on TS was not significant. Comparisons of measurements made with vertical and tilted transducers demonstrated a small but significant effect of tilt angle on TS.

Keywords: cage experiment, swimbladder, capelin, tilt angle, condition, maturation.

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Introduction

The capelin *Mallotus villosus* is a small, pelagic and planktivorous fish with a circumpolar Arctic distribution (Vilhjálmsson, 1994). The Barents Sea capelin stock has been exploited since the 1950s (Olsen, 1968; Gjøsæter, 1998) and to date, acoustic surveys and information from catch statistics have provided the only information available on stock status (Toresen *et al.*, 1998). Despite the importance of acoustic target strength (TS) in relating echo-integrator signal intensity to fish density, relatively few measurements have been made of capelin TS (Olsen and Angell, 1983; Dommasnes and Røttingen, 1984; O'Driscoll and Rose, 2001; Jørgensen and Olsen, 2002).

Capelin belong to the family Osmeridae and have a physostomous gas bladder (Fahlén, 1968). The swimbladder is considered to be responsible for most of the fish's acoustic-backscattering energy (Midttun and Hoff, 1962; Foote, 1980) and consequently its TS. Natural variations in swimbladder volume and shape may cause variations in fish TS. The important factors that are assumed to alter the TS significantly are stomach content, gonads, body-fat content, pressure (Ona, 1990; Ona *et al.*, 2001) and tilt angle (Nakken and Olsen, 1977; Olsen and Angell, 1983). To date length and weight have been found to be major determinants of capelin TS measured *in situ* and fish in better condition had lower TS independent of length (Rose, 1998). Rose suggested a TS model that includes length and weight:

$$TS = 68.6 \log L\,(cm) - 15.2 \log W\,(kg) - 157.3. \qquad (1)$$

According to Huse (1998), the life history of capelin may be sex-specific: while males follow a semelparous batch-spawning strategy, females are iteroparous. These predictions are supported by males having a lower gonadosomatic index than females.

This paper reports recent *ex situ* TS experiments on Barents Sea capelin and evaluates the possible effects of the swimbladder size and condition and of the gonads on the TS of pre- and post-spawning capelin.

Materials and methods

A cage experiment was carried out in a net pen at the fish-farming plant of the Tromsø Aquaculture Research Station on Ringvassøy, an island lying northwest of Tromsø in northern Norway. The experiment took place in the summer of 2000 and the springs of 2001 and 2002. The capelin had been captured from the Barents Sea stock during the spawning migration off the coast of Finnmark in northern Norway. The fish were caught in March using a pelagic trawl and were transported for 20 h to the research station in a tank with oxygenated water. They were kept in large tanks at the station, and were fed from March until they were transferred to the net pen. The fish were allowed access to the surface for 30 minutes before the net pen was lowered. The measurements lasted from 4 to 30 h depending on the behaviour of the fish.

Jørgensen and Olsen (2002) describe the experimental set-up in detail. The experimental net pen is shown in Figure 1. The capelin were allowed to move freely between depths of 4 and 10 m. The echo from the net roof was gated out unless the echo was less than −70 dB in TS. Smaller echoes of the net roof were ignored because they were insignificant compared to the echo from the capelin.

A calibrated split-beam echosounder enables the position of the target within the acoustic beam to be determined (Foote *et al.*, 1986), and this information enables us to track individual fish in the acoustic beam (Brede *et al.*, 1990). The TS measurements were made using a portable SIMRAD EY500 38 kHz split-beam echosounder system (SIMRAD, 1999). The electronic equipment was located in a dry laboratory ashore because the echosounder was connected by a 150-m long cable to the split-beam transducer (SIMRAD ES 38-12). Most measurements were made vertically but for some capelin the transducer was also tilted 15 or 20° in order to acquire TS information from a wider range of tilt angles. Temperatures were between 3 and 8°C during the experiment, while salinity ranged from 31 to 33.

The 38 kHz echosounder system was operated at 1 ms pulse duration and medium bandwidth. Calibration and performance tests during the experiment were done by placing a 60-mm diameter copper sphere in the acoustic beam (Figure 1). Calibration took place at a depth of 6.5 m at 1.0 and 0.2 s^{-1} (0.13 s^{-1} in 2000) ping rates, using the standard reference–target method (Foote and MacLennan, 1984; MacLennan and Svellingen, 1989). There were no major changes in calibration between 2000 (Jørgensen and Olsen, 2002), 2001 and 2002 (Table 1). TS gain from the calibration in 2002 was adjusted by 0.40 dB before TS data were collected at the 0.2 s ping interval.

The selection of a particular data set was based on its appearance on the echogram. Data acquisition was limited to targets with normalized echo lengths between 0.8 and 1.8 ms, target-position gain compensation <6.0 dB, maximal phase deviation 3.0 steps (SIMRAD, 1999) and with the minimum TS values equal to −70 dB. The TS measurements were made at a range of 3.2–8.7 m from the transducer, and were corrected for the effect of range delay (r_d) during post-processing by addition of the term:

$$\Delta TS = 40 \times \log((r_f - r_d)/r_f) - 40 \times \log((r_s - r_d)/r_s), \quad (2)$$

where r_f is the range of the fish, r_s the range of the standard target used in the calibration and r_d is a range delay of 0.30 m, as recommended by SIMRAD (Ona *et al.*, 1996).

In order to improve the signal-to-noise ratio an off-axis, cut-off beam angle of 5° was chosen in the scrutinizing procedure. After scrutinizing all data on single fish using scrutinizing software developed by the Institute of Marine Research (IMR) in Bergen, echo traces were isolated by means of the TRACKING software package (Ona and Hansen, 1991). The selected parameters for single fish tracks were a minimum of five detections, one missing value being permitted. The tracking output files were reformatted and imported to SYSTAT (SPSS Inc.) and MATLAB (Math Works Inc.) for final statistical analysis.

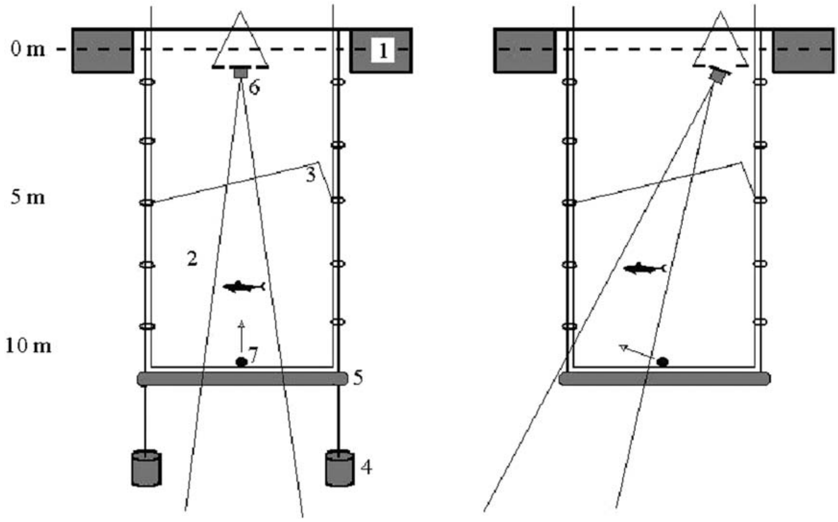

Figure 1. Schematic overview of the experimental set-up: (1) pier, (2) net pen, (3) net roof, (4) weight, (5) air-filled aluminium frame, (6) split-beam transducer and (7) calibration sphere. The arrow next to the calibration sphere shows how the sphere could be moved into the acoustic beam. The panel on the left illustrates an experiment with a vertical transducer while the right panel shows an experiment with a tilted transducer.

Table 1. Parameter settings and calibration parameters for the EY500 system.

Parameter	Date (2001–2002)				
	23 March	23 March	22 May	22 May	12 March
Sound speed ($m s^{-1}$)	1463	1463	1467	1467	1460
Ping rate (s)	1	0.2	1	0.2	1
Range (m)	6.5	6.5	6.5	6.5	6.5
RMS (dB)	0.10	0.11	0.10	0.12	0.09
TS gain (dB)	21.1	20.7	21.0	20.6	20.9
3 dB beam width (deg)					
Athwartship	12.1	12.2	12.0	12.3	12.4
Alongship	12.4	12.5	12.4	12.5	12.7
Offset angle (deg)					
Athwartship	−0.23	0.03	0.06	0.01	0.04
Alongship	−0.23	−0.02	−0.05	−0.02	0.04

The tilt angle was estimated from the movement of the fish in all accepted echo traces. The tilt angle, ω_n, between the line of movement from ping n − 1 to ping n and the face of the transducer was computed according to Jørgensen and Olsen (2002). The assumption about tilt angle and swimming direction being the same requires that the fish is not tilted in the direction of movement. With a vertical transducer, ω_n equals the tilt angle relative to the sea surface. The mean tilt angle and the standard deviation of the tilt angle were estimated for each fish. The mean TS ($\langle TS \rangle$) was computed from the mean of the acoustic-backscattering cross-section. The condition factor was computed from total length and weight (W) minus gonad weight (GW) in g:

$$K = (W - GW) \times L^{-3} \times 100. \quad (3)$$

General linear models were used to estimate the effects of log(length cm), log(weight kg) or log(gonad weight kg), mean tilt and the standard deviation of the tilt angle on $\langle TS \rangle$. A stepwise-deletion model was used to select variables influencing $\langle TS \rangle$. The subset model was then tested at the 5% level.

After the TS had been measured, each capelin was killed and immediately frozen at −20°C. The frozen capelin from the experiments in 2001 and 2002 were X-rayed (Figure 2). The length and width of the swimbladder and gas bubbles in the oesophagus were measured on lateral X-ray images of each individual fish and the volume was estimated, assuming an approximately ellipsoidal shape:

$$V = \frac{4}{3}\pi r_l r_w^2, \quad (4)$$

where r_l and r_w are half the swimbladder length (SBL) and width, respectively.

Total gas volume was estimated by adding the volumes of the swimbladder and gas bubbles. SBL measured through X-rays is dependent on air being present in the swimbladder, and therefore is affected by air moving into the oesophagus. Measurements of SBL were accepted only if the fish had been alive at the end of the experiment and gas bubbles in the oesophagus did not exceed 10% of the total gas volume. A simple linear model based on SBL was used to estimate the effect of SBL on $\langle TS \rangle$ for the capelin measured in 2001 and 2002.

$$\langle TS \rangle = a \log(SBL) + b. \quad (5)$$

Results

Successful TS measurements were made on four capelin in June and July 2000, on 17 capelin from March to May 2001 and on six fish in March and April 2002 (see Table 2).

$\langle TS \rangle$ for the 27 capelin measured with a vertical transducer and for some fish measured with a tilted transducer are shown in Table 2. The tilt angle for all 27 capelin estimated with a vertical transducer, had a mean value of −3° and a mean standard deviation of 13°.

The capelin used in the experiment had stomachs with little or no food content. Five fishes died during the experiment after providing some TS data, among them were the two females with the lowest condition factors. Condition factors were higher in males than females, and in females TS was negatively correlated to condition ($r^2 = 0.33$, see Figure 3).

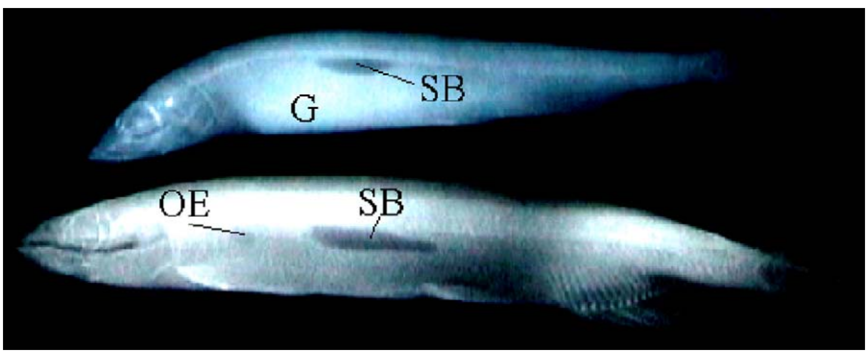

Figure 2. X-ray image of a female (upper image, F208) and a male (lower image, M224). The swimbladders (SB) are shown. The small gas bubble (OE) in the oesophagus of the male could be seen more clearly on the negatives. The female has rather big gonads (G).

Table 2. Experimental measurements of TS of individual female (F) and male (M) capelin in a net pen by date. Length (L), swimbladder length (SBL), swimbladder volume (SBV), weight (W) and gonad weight (GW) are given. Ta shows whether the transducer was vertical (0°) or tilted (15–20°). N shows the number of measurements. The mean tilt angle (⟨θ⟩ ± s.d. θ) was relative to the face of the transducer, and mean TS (⟨TS⟩) is given. Tilt-angle distributions employing a tilted transducer are shown in parentheses. X-rays were not made of F049–054. SBLs are shown in parentheses if the volume of gas bubbles in the oesophagus exceeded 10% of the estimated total gas volume.

Date	Nr	L (cm)	SBL (cm)	SBV (ml)	W (g)	GW (g)	Ta (deg)	N	⟨θ⟩ ± s.d. θ (deg)	⟨TS⟩ (dB)
30.06.00	F049	17.1			17.7	1.1	0	943	−4 ± 19	−46.0
							15	267	(−1 ± 18)	−47.0
01.07.00	F050	17.7			22.0	0.2	0	138	−3 ± 14	−49.9
04.07.00	F053	18.0			25.8	0.4	0	103	1 ± 22	−49.6
05.07.00	F054[a]	15.7			12.6	2.0	0	116	−1 ± 17	−47.3
28.03.01	M202	19.6	2.8	0.3	41.2	0.5	0	50	10 ± 12	−46.4
							20	331	(4 ± 16)	−47.9
29.03.01	M203	17.7	2.5	0.1	28.6	0.2	0	137	1 ± 18	−46.3
							20	187	(−14 ± 22)	−48.4
02.04.01	F205	17.6	1.7	0.2	29.5	9.4	0	56	−5 ± 13	−52.6
							20	65	(5 ± 19)	−52.9
03.04.01	F206	17.5	(0.9)	0.3	30.3	9.9	0	79	10 ± 16	−49.9
							20	13	(12 ± 9)[b]	−50.7
04.04.01	F207[a]	17.1			24.1	5.5	0	17	−14 ± 14	−50.7
	F208	16.8	1.9	0.3	27.8	9.1	0	87	−10 ± 20	−49.1
05.04.01	F209	16.3	(1.8)	0.3	21.0	7.0	0	34	7 ± 18[b]	−50.0
	M210	17.8	1.4	0.1	32.2	0.1	0	318	0 ± 11	−50.9
06.04.01	F211	17.7	(1.4)	0.2	30.5	8.5	0	29	18 ± 5	−48.0
							20	290	(−3 ± 18)[b]	−50.7
	M212[a]	18.9			45.0	0.7	0	94	3 ± 15	−49.9
18.04.01	M220	17.2	2.8	0.3	27.1	0.1	0	88	−7 ± 11	−45.2
24.04.01	M223	18.1	2.2	0.2	30.9	0.4	0	114	4 ± 10	−50.4
							20	214	(−1 ± 19)[b]	−50.4
25.04.01	M224	19.5	3.0	0.8	46.5	0.6	0	109	0 ± 10	−45.5
							20	313	(−6 ± 16)	−46.7
02.05.01	M226	17.9	2.5	1.0	32.9	0.4	0	26	1 ± 12	−45.4
10.05.01	M228	19.4	(2.4)	0.5	41.5	0.6	0	32	−1 ± 4[b]	−45.7
							20	127	(3 ± 17)	−47.0
11.05.01	F229	16.4	1.3	0.1	25.5	8.0	0	12	−11 ± 15[b]	−52.6
	M231[a]	18.2			36.6	0.3	0	158	−6 ± 12	−51.5
25.03.02	F235[a]	15.5			13.8	3.5	0	54	−10 ± 10	−43.1
26.03.02	F236	17.6	(0.8)	0.2	27.8	7.3	0	337	−1 ± 14	−52.2
27.03.02	F237	17.0	(2.5)	0.3	22.5	4.6	0	10	−24 ± 3	−48.2
03.04.02	M239	17.0	(1.1)	0.4	28.9	0.9	0	52	−3 ± 13[b]	−48.7
04.04.02	F240	17.5	1.8	0.3	18.0	0.7	0	54	−7 ± 14[b]	−49.9
	M241	18.2	1.6	0.1	35.3	0.8	0	94	−16 ± 19	−51.8

[a]Fish that died in the experimental net pen after providing some TS data are marked.
[b]Tilt-angle distributions that are bi- or trimodal.

The data were split into that for males and females and general linear models in SYSTAT (SPSS Inc.) were used to estimate the effects of the individual variables on TS. The probability level for removal of variables was set at 0.25. At each step the variable with the lowest explanatory power was removed and the revised model was refitted. Log(length) had the lowest explanatory power for females and was the first variable to be removed. All variables except log(weight) were removed. Log(weight) explained 45% of the variation in the TS data ($p < 0.01$). Figure 3 shows the best-fit regression for females:

$$\langle TS \rangle = -14.2 \log(\text{weight kg}) - 72.6;\ r^2 = 0.45,\ n = 15. \qquad (6)$$

The same procedure using general linear models for ⟨TS⟩ was followed, replacing weight with gonad weight. However, there was no significant effect of gonad weight on ⟨TS⟩. In fact there was no significant linear relationship between ⟨TS⟩ and any of the variables in male fish ($p > 0.1$, $n = 12$) and this was also the case when data from males and females were merged ($p > 0.1$, $n = 27$).

The estimated swimbladder volume per unit wet-body weight ranged from 0.2 to 3.0%. The results of the linear least-mean-square regression analysis of ⟨TS⟩ on SBL are shown in the scatter diagram in Figure 3. Fish with more than 10% of the gas volume of in the oesophagus have been removed from the analysis. The best-fit regression ($p < 0.0005$) was:

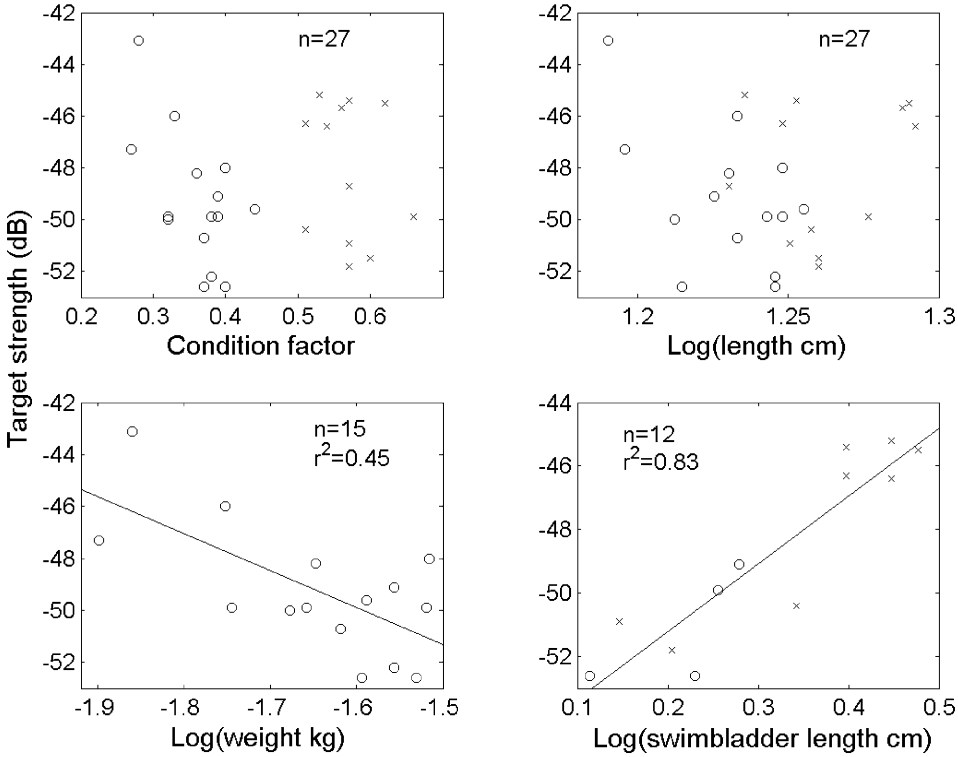

Figure 3. Upper panels show scatter diagrams with TS for capelin relative to condition factor (left) and TS relative to length (right). Crosses represent males; circles, females. Lower panels show scatter diagrams with linear regression of TS relative to weight for females (left) and TS relative to SBL (right).

$$\langle TS \rangle = 21.4 \log(\text{swimbladder length cm}) - 55.5; \quad r^2 = 0.8, \; n = 12. \tag{7}$$

The mean acoustic-backscattering cross-section measured using a tilted transducer was significantly lower than that measured with a vertical transducer (Friedman test, $p < 0.01$, $n = 9$). TS observations in relation to estimated tilt angle are shown for a maturing male (M224) and a maturing female (F205) in Figure 4. Data collected with the vertical and tilted transducer were merged. The smoothed lines in Figure 4 describe the main trends in the data. TS for the male are highest at about $-6°$ tilt angle possibly because the swimbladder is slightly tilted inside the fish (Figure 2).

Discussion

The rather large net pen permitted natural free-swimming behaviour but led to a rather small sample size for some fish. In this experiment, TS might be affected by fish behaviour, mainly due to changes in orientation. Olsen and Ahlquist (1989) observed that the tilt angle of capelin (0–5°) in a small cage did not change significantly when the depth was rapidly increased from 5 to 50 m, indicating that the swimming direction of capelin is in the direction of movement and not buoyancy-dependent as, according to Olsen and Ahlquist (1989), was the case for the tilt angle of herring. The mean tilt angle of all the capelin used in the experiment ($-3 \pm 13°$) reflects the fact that capelin exhibited a wide range of tilt angles although the mean angle did not deviate greatly from the horizontal. This has also previously been reported *in situ* from photographic estimates (Carscadden and Miller, 1980). The mean and standard deviation of the tilt angle of each individual capelin varied from fish to fish, probably due to individual differences in behaviour, but did not have any significant effect on mean TS except when the transducer was tilted to simulate rather extreme tilt angles. Compared to species such as herring *Clupea harengus* and cod *Gadus morhua* (Nakken and Olsen, 1977) at 38 kHz the effects of tilt angle on TS are fairly small for capelin as these results show (see also Jørgensen and Olsen, 2002). The rather narrow range of capelin TS will reduce the effect of behaviour on TS to some extent.

Capelin are physostomous and the gross morphology of the gas bladder is described by Fahlén (1968). The gas bladder of capelin is of the usual salmonid shape and opens into the oesophagus. It is not known whether the individual

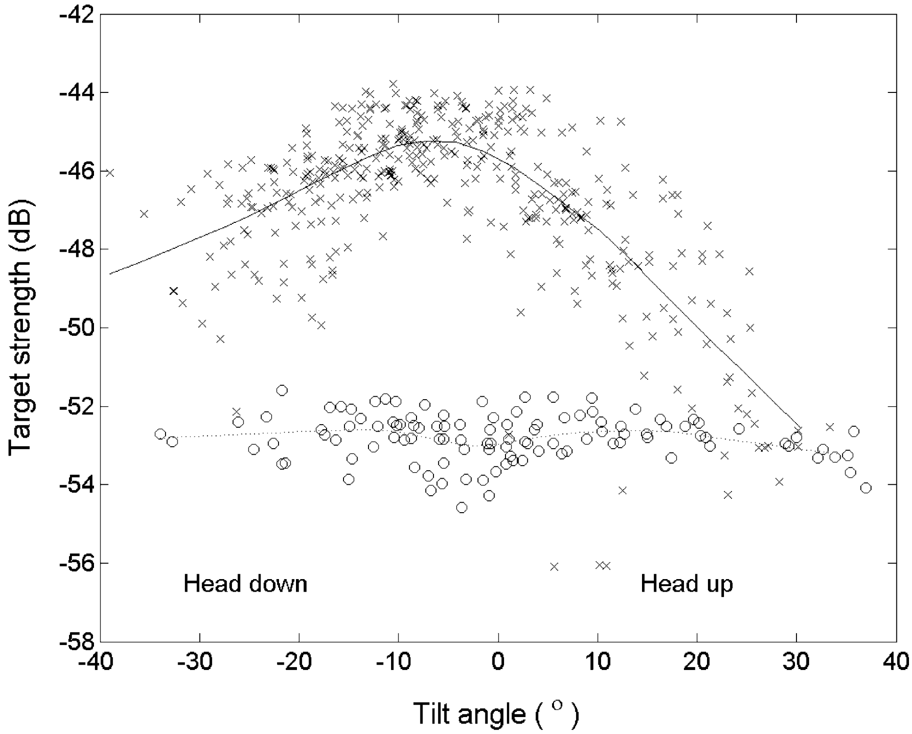

Figure 4. Target-strength observations relative to estimated tilt angle for a 17.6 cm female (circle) and a 19.5 cm male (cross). The smoothed lines describe the main trends in the data.

differences in swimbladder volumes and lengths in the fish in this experiment reflect the true situation in capelin *in situ*. When frightened, physostomous fish (salmonids) dive into deeper waters and as much as 34% of the swimbladder gas could be ejected, probably as a result of the active contraction of the swimbladder muscles (Fänge, 1983). The swimbladder size of the capelin might have been affected if gas was ejected when the capelin was lowered from the surface to the measuring depth, or when the capelin was lifted out of the net pen and killed.

Gas may also have been lost due to the method of freezing. In some individuals the X-rays showed bubbles of gas in the oesophagus. This gas appears to have escaped from the swimbladder and is a potential source of error in the measurements of swimbladder size. However, the logarithm of SBL in this experiment does explain about 80% of the variation in TS for fish in which little or no gas appeared to have escaped from the swimbladder to the oesophagus. SBL has been known to be less affected than swimbladder width by changes in swimbladder volume. Ona (1990) decreased the swimbladder volume of cod in pressure-tank experiments, and found that most of the change in swimbladder shape took place in the vertical plane.

The lack of measurement of fat content in this experiment leaves weight and length as the only indicators of condition. In female capelin with a rather narrow length distribution the logarithm of weight was significantly negatively related to TS, explaining about 45% of the variation. The negative effect of weight on TS could be due to higher fat content giving additional buoyancy and less need for swimbladder volume.

In contrast to females, we found no significant linear relationship in males between ⟨TS⟩ and any of the variables other than SBL, indicating that the sexual dimorphism that exists between mature females and males (Huse, 1998) may also affect the acoustic properties of this species.

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