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# Depth dependence of target strength of live kokanee salmon in accordance with Boyle's law

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The target strength (TS) of fish varies with a number of factors, especially the presence or absence of a swimbladder. This study investigated the effect of the swimbladder on the TS of live kokanee (*Oncorhynchus nerka*) in relation to depth. Experiments were conducted at Lake Kuttara, Hokkaido, Japan, which is abundant with kokanee. Fish samples were caught with a fishing net. The live fish were suspended on the sound beam axis, and tilted from −50° (head-down aspect) to +50° (head-up aspect). The dorsal aspect TS functions were measured at 50 kHz. Measurements were performed when the fish were forced to change depth rapidly. The TS values were measured as a function of tilt angle and depth, and the maximum dorsal aspect TS ($TS_{max}$) values and the averaged dorsal aspect TS ($TS_{avg}$) values were calculated and compared. $TS_{avg}$ values were calculated with respect to fish tilt-angle distribution, which was assumed to have a mean value of −5° and a standard deviation of 15°. Both $TS_{max}$ and $TS_{avg}$ decreased with depth in accordance with Boyle's law, i.e. a reduction rate of 6.7 dB per 10 atm was observed.



Key words: Boyle's law, depth dependence, echosounder, kokanee salmon, swimbladder, target strength.

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## Introduction

The target strength (TS) of fish is a prime factor for quantitative and qualitative assessment of their stocks by acoustic techniques. The TS varies with a number of factors, including fish size, fish activity, orientation, behaviour, and structural components of the body. Among these, the swimbladder, which is proportional to fish size and depth, is recognized as having the most important effect on the TS.

Foote (1980b), by direct comparison of gadoids and mackerel, which possess and lack a swimbladder, respectively, showed that more than 90% of the backscattered energy comes from the swimbladder. Mukai *et al.* (1994) also showed that the dorsal aspect TS values of the silver pomfret *Pampus argenteus* (with no swimbladder) were lower by about 7–11 dB at 25 and 100 kHz than two other similar fish (yellow sea bream, *Dentex tumifrons*, and whitefin crevalle, *Kaiwarinus equula*) with swimbladders. Furusawa (1988) investigated the general trends of the TS of fish or other organisms by using prolate spheroidal scattering models. He concluded that almost all the backscattered energy is attributed to gas-filled structures.

In the case of fish with a swimbladder whose volume changes with the ambient pressure, the TS will depend upon the depth of the fish. Edwards and Armstrong (1984) studied these effects by examining a number of fish enclosed in a cage. The cage was repeatedly lowered and raised while the TS of the fish was continuously monitored. When the pressure was increased, the TS of bladder fish decreased, but in fish without swimbladders, the TS remained the same.

The purpose of the present paper is to investigate the effect of the swimbladder on the TS of live individual fish in relation to depth.

## Materials and methods

The experiments were performed in Lake Kuttara, located around 42°30′N, 141°11′E, with an area of 4.34 $km^2$ and a maximum water depth of 148 m. In this lake, kokanee (*Oncorhynchus nerka*) are the dominant species. From the acoustic point of view (Edwards and

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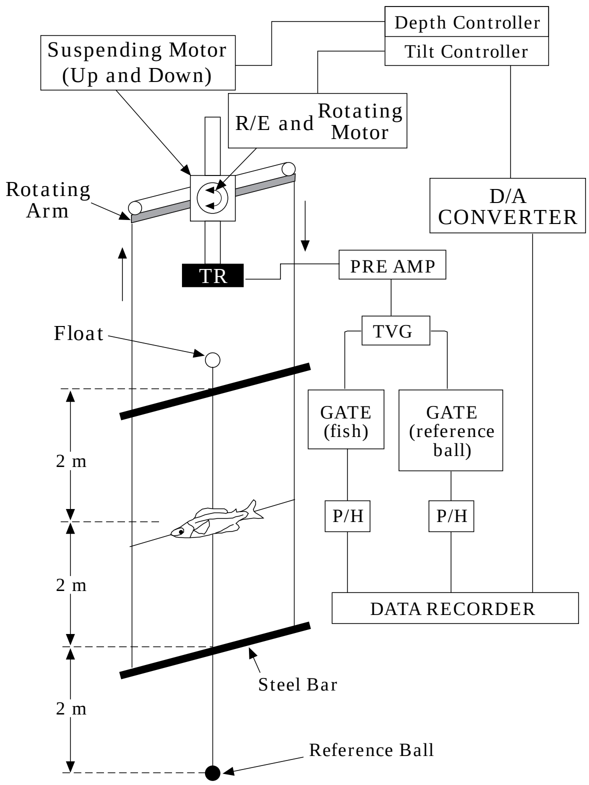


Figure 1. Automatic suspension and rotation system for fish, and block diagram of data acquisition.

Armstrong, 1984), kokanee can be divided into the open swimbladder (physostomatous) category. Fish samples were caught by gillnet and set-net. Fifty kokanees were used in TS measurements. The ranges of total length and body weight of these fish were 16.0–32.9 cm and 32–400 g, respectively. Fish were placed in a plastic cage for about 2 d at the surface to adapt to the surrounding conditions as much as possible. The fish were anaesthetized with MS222 before TS measurements and kept in the central part of the sound beam by a frame of thin nylon monofilament.

Figure 1 shows the automatic suspension and rotation system for fish used in the experiment. The fish rotating speed was about 30° $min^{-1}$. The reference target, which was a 38 mm diameter high-carbon steel sphere, was positioned 2 m beneath the bottom steel bar with a monofilament nylon line to calibrate fish echoes.

The dorsal aspect TSs were measured by 50 kHz. The pulse duration and repetition rate were 1 ms and 60 pulses $min^{-1}$, respectively. The beam width of the transducer was 33°. The output signal of the receiver was compensated by a TVG amplifier. The fish was tilted from −50° (head-down aspect) to +50° (head-up aspect) at 0.5° intervals using the automatic rotating system.

To compare the TS of individual fish, two TS measures were used. These included the maximum dorsal aspect TS ($TS_{max}$) value and the averaged dorsal aspect

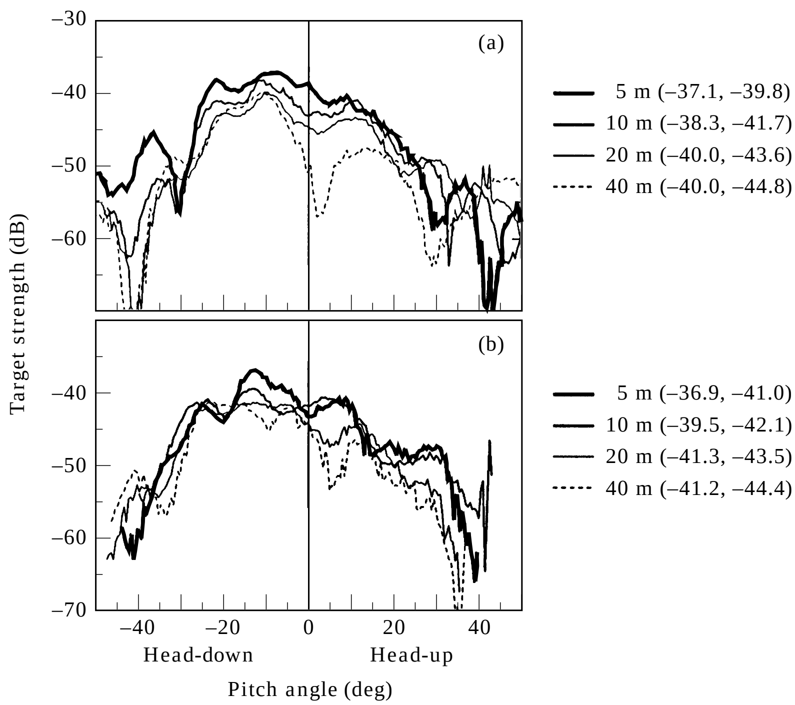


Figure 2. Depth dependence of the dorsal aspect target strength function of two kokanees (a: 18.6 cm, b: 19.8 cm) at 50 kHz. At any depth, $TS_{max}$ and $TS_{avg}$ show in figure as ($TS_{max}$, $TS_{avg}$).

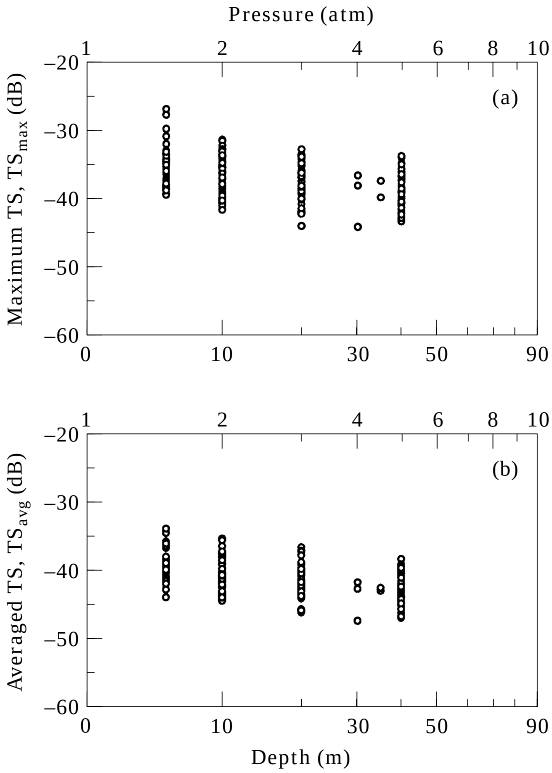


Figure 3. Comparison of maximum dorsal aspect target strength (a) and averaged dorsal aspect target strength (b) of 50 kokanees, arranged by depth.

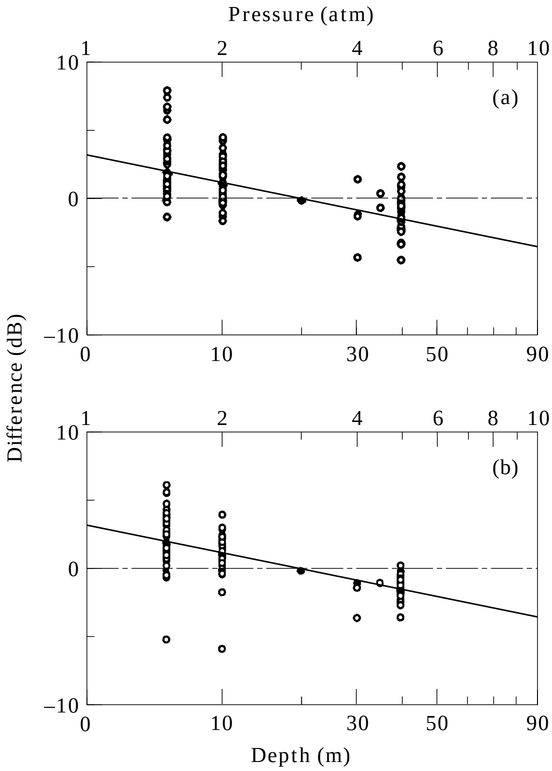


Figure 4. Normalized maximum dorsal aspect target strength (a) and averaged dorsal aspect target strength (b) based on 20 m depth, arranged by depth and pressure (P). The solid line denotes the theoretical (balloon model) line in accordance with Boyle's law, i.e. $\Delta TS = -6.7 \log P + 3.18$.

TS ($TS_{avg}$) value. $TS_{max}$ was obtained easily from the measured TS functions. $TS_{avg}$ was calculated by using the probability density function (PDF) of fish tilt angle $f(\theta)$ in Equations (1) and (2) (Foote, 1980a):

$$\sigma_{avg} = \int \sigma(\theta) f(\theta) d\theta \quad (1)$$

$$TS_{avg} = 10 \log(\sigma_{avg}/4\pi) \quad (2)$$

where $\theta$ is defined as the angle made by an imaginary line from the snout tip to the root of the tail with the horizontal plane. $f(\theta)$ was assumed to be a truncated normal distribution function. The truncations were made at $\bar{\theta} - 3S_\theta$ and $\bar{\theta} + 3S_\theta$, where $\bar{\theta}$ and $S_\theta$ denote the mean and standard deviation of tilt angle, respectively, and assumed to be $-5°$ and $15°$.

In order to change the swimbladder volume, the fish were lowered at 5, 10, 20, 40 m, and TS measurements were made rapidly in order of increasing depth.

If the fish swimbladder contracts concentrically under increasing pressure, one would expect the volume and cross-sectional area reduction to follow Boyle's law:

$$SB_v \sim P^{-1} \quad (3)$$

and

$$SB_a \sim P^{-2/3} \quad (4)$$

where $SB_v$ and $SB_a$ are the volume and area of the swimbladder, respectively, and P is the pressure in atm. The surface area (dorsal aspect) of the swimbladder increases approximately with the square of length (Gunderson, 1993). So, the relationship between the TS and ambient pressure follows the balloon model:

$$TS \sim -\frac{20}{3} \log P \quad (5)$$

Consequently, the TS reduction at P atm was about (20/3)logP (dB) compared with that of 1 atm using this balloon model.

## Results and discussion

Figure 2 shows the example of the depth-dependence of the dorsal aspect TS function. At most tilt angles, the TS tended to decrease with increasing depth. The TS peak at about $-12°$ notably decreased with increasing depth. $TS_{max}$ and $TS_{avg}$ also showed that the TS tended to decrease with increasing depth.

Table 1. Comparison of theoretical (balloon model) and observed TS values (in dB) against depth, normalized to TS at 20 m.

| Depth (m) | Balloon model | $TS_{max}$ | | | $TS_{avg}$ | | |
|---|---|---|---|---|---|---|---|
| | | Mean | N | s.e. | Mean | N | s.e. |
| 5 | +2.0 | +2.7 | 50 | 2.1 | +2.3 | 50 | 1.9 |
| 10 | +1.2 | +1.5 | 50 | 1.3 | +1.3 | 50 | 1.4 |
| 20 | 0 | 0 | 50 | — | 0 | 50 | — |
| 40 | − 1.5 | − 0.7 | 42 | 1.3 | − 1.1 | 42 | 0.8 |

s.e. = Standard Error.

The $TS_{max}$ and $TS_{avg}$ for all 50 fishes are plotted as a function of depth and pressure in Figure 3, which shows that the TS tended to change inversely with depth.

To show the tendency of decreasing TS with increasing depth, the $TS_{max}$ and $TS_{avg}$ were normalized to the value at 20 m depth. This depth corresponds to the swimming layer of kokanee. A decrease in the ratio of the TS based on 20 m depth is shown in Figure 4. The solid line denotes a theoretical line predicted by the balloon model, as shown in Equation (5). Mean values and standard errors of normalized TS are summarized in Table 1. It is clear that the mean value of each TS decreases with increasing depth in accordance with the balloon model.

Observations made by Blaxter *et al.* (1979) showed that the swimbladder volume and the cross-sectional area of the herring swimbladder were reduced with increasing pressure. However, the swimbladder did not contract concentrically, and the volume reduction was more than that predicted by Boyle's law, while the reduction of the cross-sectional area of the swimbladder was less than that predicted by Boyle's law for uniform compression. Ona (1990) has also shown that the swimbladder volume follows Boyle's law with increasing pressure, but the dorsal area of the bladder does not follow the law at moderate pressure. As shown in Figure 4, this may be why the experimental values were a little scattered around the model line.

From these experiments, we conclude that the major contribution to scattering from bladder fish is due to the swimbladder. The fact that TS varied with depth is important for those species which perform daily vertical migration or with an avoidance reaction. It is believed that the TS of physostomatous fish are highly dependent on depth. Because they typically lack a gas-secreting mechanism (Gunderson, 1993), the TS does not recover even if fish stay at one depth for a long time. It is therefore suggested that depth adjustment of the TS in accordance with Boyle's law might be applied to physostomatous fish.

Finally, to obtain the TS for use in abundance estimation, the TS of free-swimming fish must be measured at the same time, location, and ship speed as applied during the survey.

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