AACL BIOFLUX

Aquaculture, Aquarium, Conservation & Legislation
International Journal of the Bioflux Society

Measurement and numerical model of fish target strength for quantitative echo sounder

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Abstract. This paper discussed the target strength (TS) of fish for a quantitative echo sounder. Experiments were conducted in a water tank using matures *Cyprinus carpio* sp. Measurements were conducted using 50 kHz and 200 kHz frequencies of echo sounder instrument and the tilt angle of tethered fish. Swimbladder size and shape were measured using X-ray and digitized. The theoretical target strength was numerically computed using the prolate spheroidal modal series (PSMS) and compared using the echo sounder measurement. The results showed that TS strongly depends on the orientation of the fish. The increasing of vertically averaged TS was followed by the increasing tilt angle. Prolate Spheroidal Modal Series (PSMS) computation showed TS values depend on operating acoustic frequency of sonar system.

Key Words: acoustic, target strength, sonar, prolate spheroidal modal series (PSMS).

Introduction. Fish target strength (TS) is an important factor for designing sonar system or scientific echosounder and as a scaling factor for quantitative fish stock measurement (Foote 1980). Therefore, until now many scientists had worked in this area (Nishimori et al 2009; Manik 2015). TS of fish depend on many factors such as morphology, behavior, and acoustic frequency of sonar instrument. In the same species, the TS are variable due to change in fish length, tilt angle, and swimbladder presence. According to Simmonds & MacLennan (2005), the swimbladder of fish contributes 90-95% of acoustic energy of backscattering, therefore bladder morphology was important for TS measurement. Accurate determination of target strength is essential to fisheries acoustics, since it allows conversion of backscattering to fish biomass. The swimbladder is the most important factor affecting acoustic backscattering (Weston 1967; Furusawa 1988).

TS is a logarithmic measure of the proportion of the incident energy which is backscattered by the target (Simmonds & MacLennan 2005). To understand the nature of TS, it is better to begin with the related quantity the backscattering cross section, which is a more meaningful parameter in physical terms. Acoustic backscattering cross section is measured in units of area, square metres in SI units. It is defined in terms of the intensities of the incident and the backscattered waves (Simmonds & MacLennan 2005).

TS values are determined using acoustic instrument and by theoretical model. Using acoustic instrument, we could not rely wholly on the measurements. The problem arises because fishes are complex scatterers acoustically in shape, orientation, and structure. Also there are more species of fish and sometime mixed with other biota such as zooplankton and micronekton (Stanton et al 2010a). Hence, we use a theoretical model to predict TS and to interpolate or extrapolate of measured data using acoustic instrument.

TS model has been applied for study of the fish body or swimbladder (Medwin & Clay 1998). Unfortunately, this model cannot explain the results obtained by precise measurement. For zooplankton target strength, several researchers used fluid sphere model, but this could not give good prediction (Horne & Clay 1998; Tang et al 2009; Smith el al 2012). Therefore, more accurate and complex models have been proposed in this study. Until now, only a few measurements have been conducted to compute the fish orientation dependent on TS because it was difficult to measure the TS value at different orientation. We adopt the prolate spheroid modal series (PSMS) model as the acoustic backscattering model of fish, compute the backscattering amplitude and compare the computed results with measurement data.

Material and Method

Measurement of fish target strength in a laboratory tank. Data acquisitions were conducted on March-June 2015 in Ocean Acoustics and Instrumentation Laboratory Department of Marine Science and Technology Bogor Agricultural University (IPB) Indonesia. The specifications of this laboratory were a cylindrical water tank of 3.2 m in depth and 6 m in diameter filled with freshwater (Figure 1). TS data were collected with a fish finder (Cruz Pro Sounder) connected to a 50 kHz and 200 kHz transducer with a 3 dB beam width of 12^o and 2 ms pulse width. A transducer was suspended at mid water depth in the tank facing vertically toward the fish. The echosounder was calibrated using a 38.1 mm diameter tungsten carbide sphere (Simrad 2012; Demer 2015).

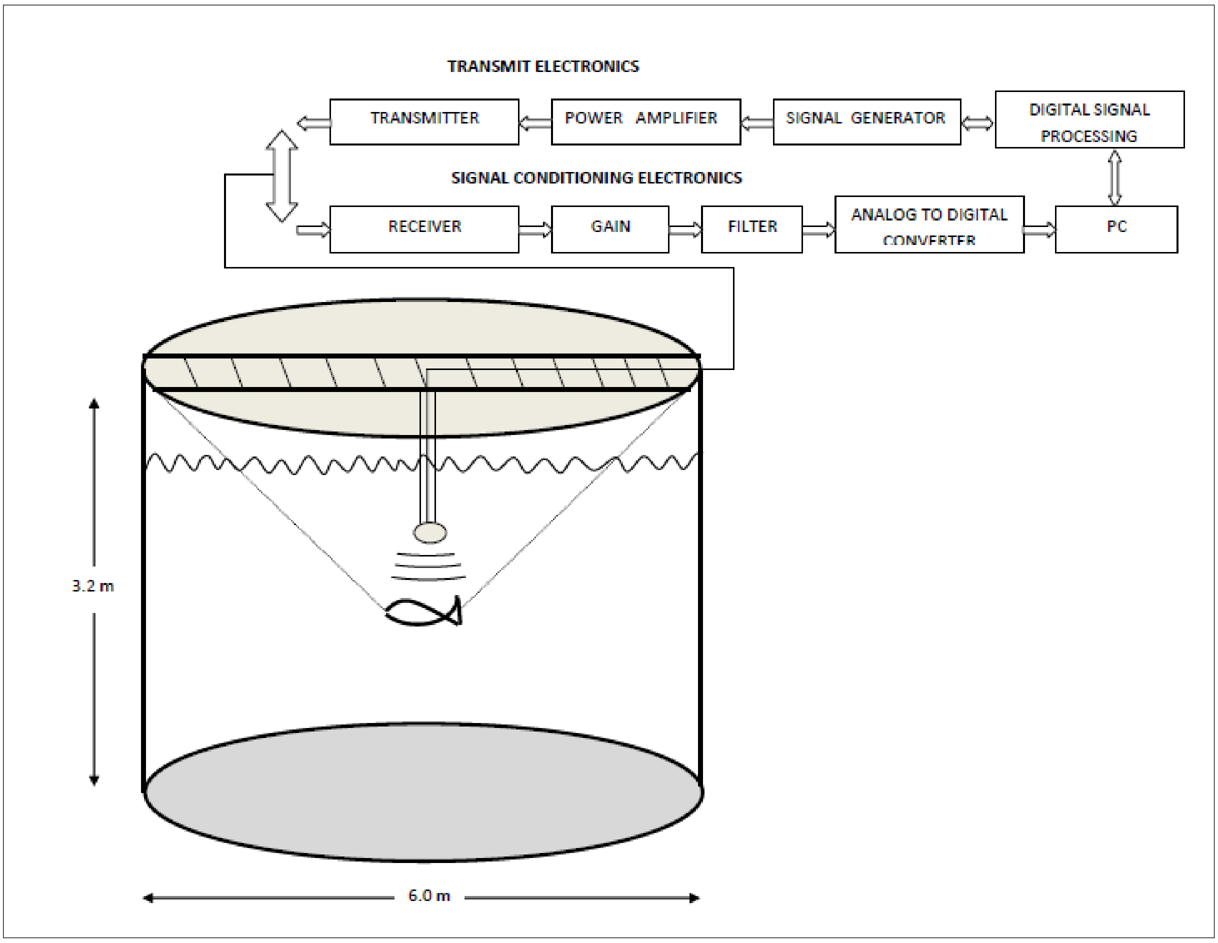

Figure 1. Experimental setup to measure TS of fish in a water tank.

The total 20 specimens of *Cyprinus carpio* with 45.9 to 77.4 cm in fish length and 80 g in average body weight were used for data acquisition. A soft X-ray imaging system was used to obtain morphological data of fish. Dorsal and lateral shape of swimbladder and fish body were digitized using image processing software in Matlab. Digitized data used to compute the theoretical TS using PSMS model. The fish was suspended using a pair of nylon monofilament lines of 0.2 mm diameter with two hooks. The hooks were attached to the head and the caudal of fish. The fish was lowered to the center of the water tank at a depth of 150 cm from the transducer.

The acoustic transducer transmits a signal with a source level SL, given in underwater dB one meter from the source. The sound energy becomes weaker as it travels toward the target, due to geometrical spreading and absorption loss. The total reduction in signal intensity is called the transmission loss TL, given in decibels. The intensity from the target echo relative to the intensity of the sound hitting the target is called the target strength TS, given in decibels. The echo intensity (EI) one meter from the target signal from a source with a source level of (Urick 1983; Medwin & Clay 1998):

$$EI \text{ (dB)} = (SL - TL) + TS \qquad (1)$$

The reflected signal travels back to the acoustic instrument, the signal intensity is again reduced by the transmission loss TL. The intensity of the returned echo (EL) at the receiver is then:

$$EL \text{ (dB)} = SL - 2TL + TS \qquad (2)$$

The noise level at the receiver is NL decibels, then the ratio of the signal level to the noise level at the receiver, called the signal-to-noise ratio (SNR), is:

$$SNR \text{ (dB)} = SL - 2TL + TS - NL \qquad (3)$$

The noise level is reduced by the array gain AG, and the SNR is increased:

$$SNR \text{ (dB)} = SL - 2TL + TS - (NL - AG) \qquad (4)$$

Computation of numerical model for fish target strength. Prolate spheroidal coordinates are a three-dimensional orthogonal coordinate that result from rotating the two-dimensional elliptic coordinate system about the focal axis of the ellipse (Figure 2). PSMS is one of the theoretical physic methods used to calculate the scattering from marine biota such as fish and zooplankton. PSMS model approximate the swimbladder as a prolate spheroid form. The major and minor axis of the prolate spheroid were calculated by the swimbladder outline. Geometries of the PSMS model was shown in Figure 2.

The backscattering amplitude in the far filed approximation are described in the form function f_∞ (Furusawa 1988):

$$f_\infty(\theta,\phi \,|\, \theta',\phi') = \frac{2}{jk_0}\sum_{m=0}^{\infty}\sum_{n=m}^{\infty}\frac{\varepsilon_m}{N_{mn}(h_0)}S_{mn}(h_0,\cos\theta') \times A_{mn}S_{mn}(h_0,\cos\theta)\cos m(\phi-\phi') \qquad (5)$$

where θ, θ' and ϕ, ϕ' are the scattering and incidence angles, respectively, ε_m is Neuman factor, $h_o = k_o\, q$ (k_o is the wave number in the surrounding water and q is the semi focal length), S_{mn} is the prolate spheroidal wave function of first kind of order m and degree n; N_{nm} is the norm; and $j = \sqrt{-1}$. The coefficient A_{mn} is determined from appropriate boundary condition [5].

The TS of fish is related to f_∞ computed as (Ye & Furusawa 1995):

$$TS(\theta) = 20\log F = 20\log|f\infty(\theta,0)(\pi-\theta,\pi)| \qquad (6)$$

where F is defined as the absolute value of the backscattering amplitude from the fish in the far field region. The computation were conducted using MATLAB program.

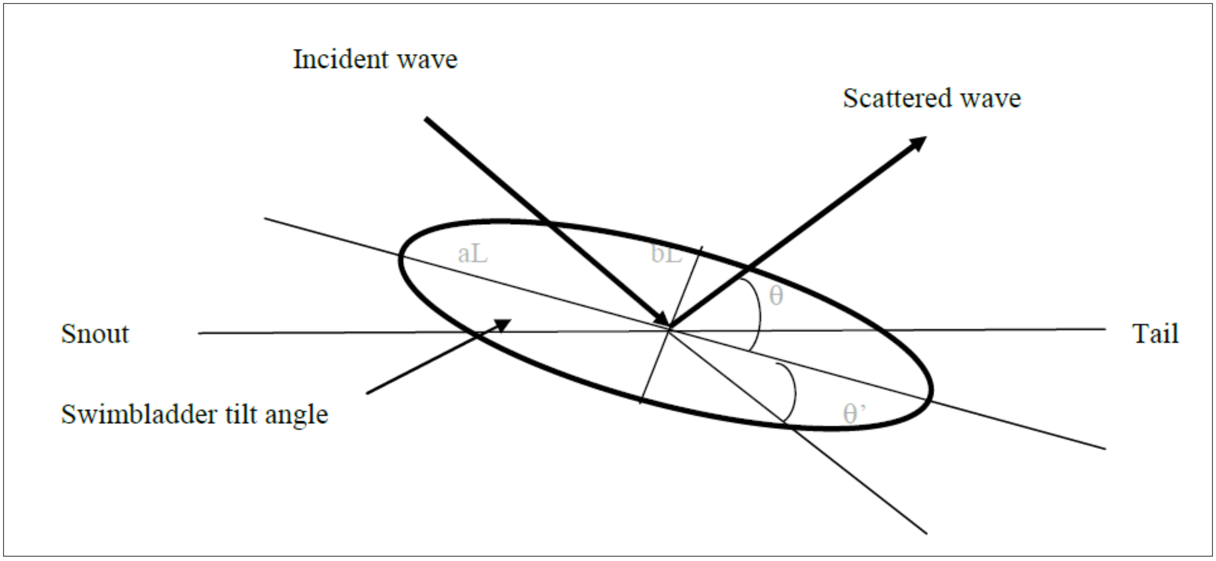

Figure 2. Swimbladder geometry for the spheroid model. Thick arrows indicate the directions of the incident and scattered waves. Posistive swimbladder tilt angles are head up.

Parameters used in the prolate spheroids models are the sound speed in seawater, which was 1530 m s^{-1}, in the swimbladder was 350 m s^{-1}, and in fish body was 1580 m s^{-1}. Density ratio between air and seawater is 0.00126, and between fish flesh and seawater is 1.06. We used 50 kHz and 200 kHz operating frequencies for acoustic measurement of fish TS. Maximum TS value against fish orientation or tilt angle were plotted. Tilt angle distribution is required to calculate the average fish TS. The mean TS is normalized by TS_{cm} resulted $TS = 20 \log FL + TS_{cm}$, where *TS* is target strength in dB and *FL* is fish length in cm.

Results and Discussion. Figure 3 shows the calibration sphere was detected in echogram. Target strength of sphere was -35.5 dB.

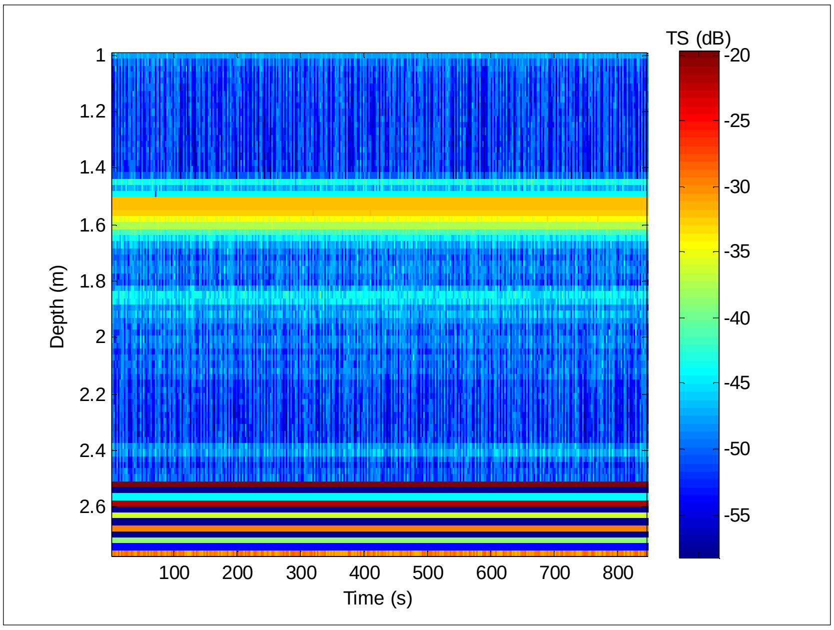

Figure 3. Sphere detected (yellow color) in acoustic calibration.

In our experiment, all the fish had a swimbladder morphology and the selected 20 fish with swimbladders in a good condition (Table 1). By this table, the swimbladder volume increases with the fish length. The obtained result is nearly equal with the previous research using side scan sonar instrument (Sawada et al 1999; Tang et al 2009).

Table 1

Fish length (FL) and swimbladder dimensions of *Cyprinus carpio* as the input for numerical computation

Specimen number	*FL (cm)*	*aL (cm)*	*bL (cm)*	*Swimbladder volume (cm^3)*
1	70.5	6.9	2.4	100.5
2	75.0	6.4	3.3	110.0
3	60.8	6.2	3.6	78.5
4	68.4	7.4	4.5	88.6
5	70.0	8.5	3.3	98.5
6	72.2	6.4	2.6	99.8
7	77.4	6.9	2.4	100.1
8	71.9	7.5	3.2	99.5
9	60.9	8.2	2.3	95.4
10	67.8	6.4	2.4	96.5
11	66.9	5.3	2.6	97.8
12	66.5	4.6	2.7	97.5
13	64.3	5.9	3.0	95.3
14	60.5	4.8	3.2	90.5
15	50.8	5.6	3.1	80.5
16	55.9	4.9	2.9	85.9
17	56.5	5.8	2.4	86.0
18	55.3	5.6	3.2	87.5
19	52.0	4.3	3.1	78.5
20	45.9	4.8	2.5	70.5

The linear relationship between TS and fish length with the correlation coefficient of 0.93 is shown in Figure 4. The increasing of fish length was followed by the increasing of TS value.

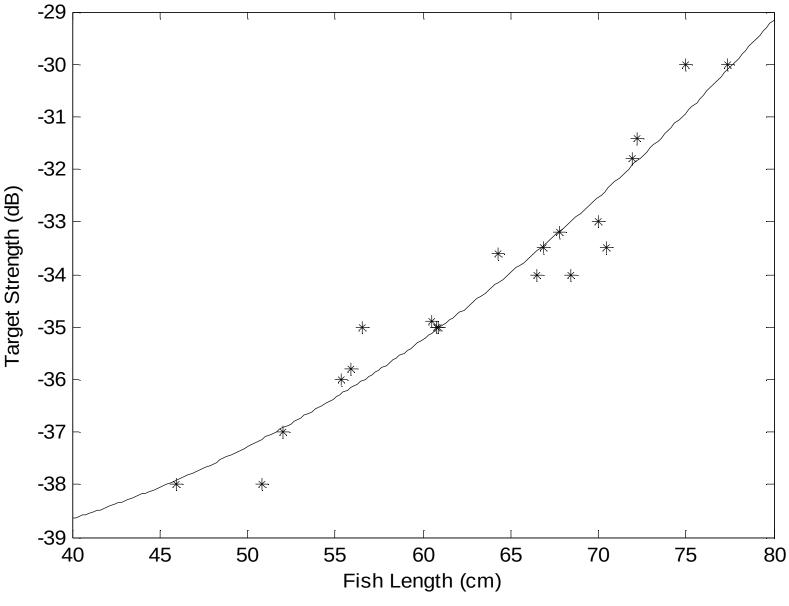

Figure 4. Target strength and fish length relation.

Figures 5 and 6 show the measured vertical TS functions at tilt angle from -90^o to 90^o. The maximum TS was found at a vertical incident angle of 0^o, and the TS decreased as the tilt angle increased. The decreasing pattern of the vertical TS changed more slightly as tilt angle increased. The maximum TS was about -39 dB. This shows that the TS pattern of fish depends highly on the fish orientation. These results were in a good agreement compared with previous researchers (Stanton et al 2010b). These figures (5 and 6) also show a comparison between the theoretical TS functions and measurement at tilt angle from -90^o to 90^o. The results show that the theoretical estimation and the measurement were in a close agreement. The theoretical model that the maximum TS was found at a vertical incidence angle at 0^o, and the TS decreased slightly with the increasing of acoustic measurement. This theoretical model shows in a good agreement with the acoustic measurement.

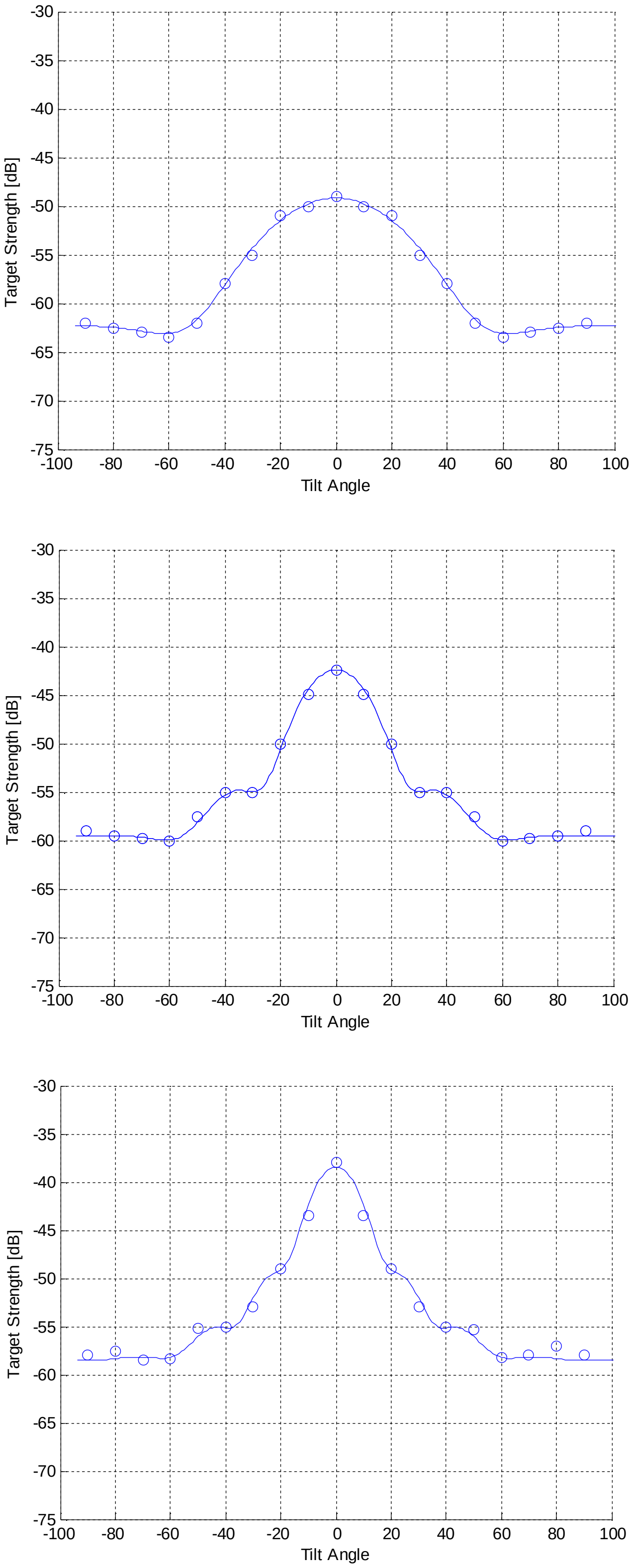

Figure 5. Measurement (o) and numerical computation (-) using 50 kHz for 10, 20, 30 cm fish length.

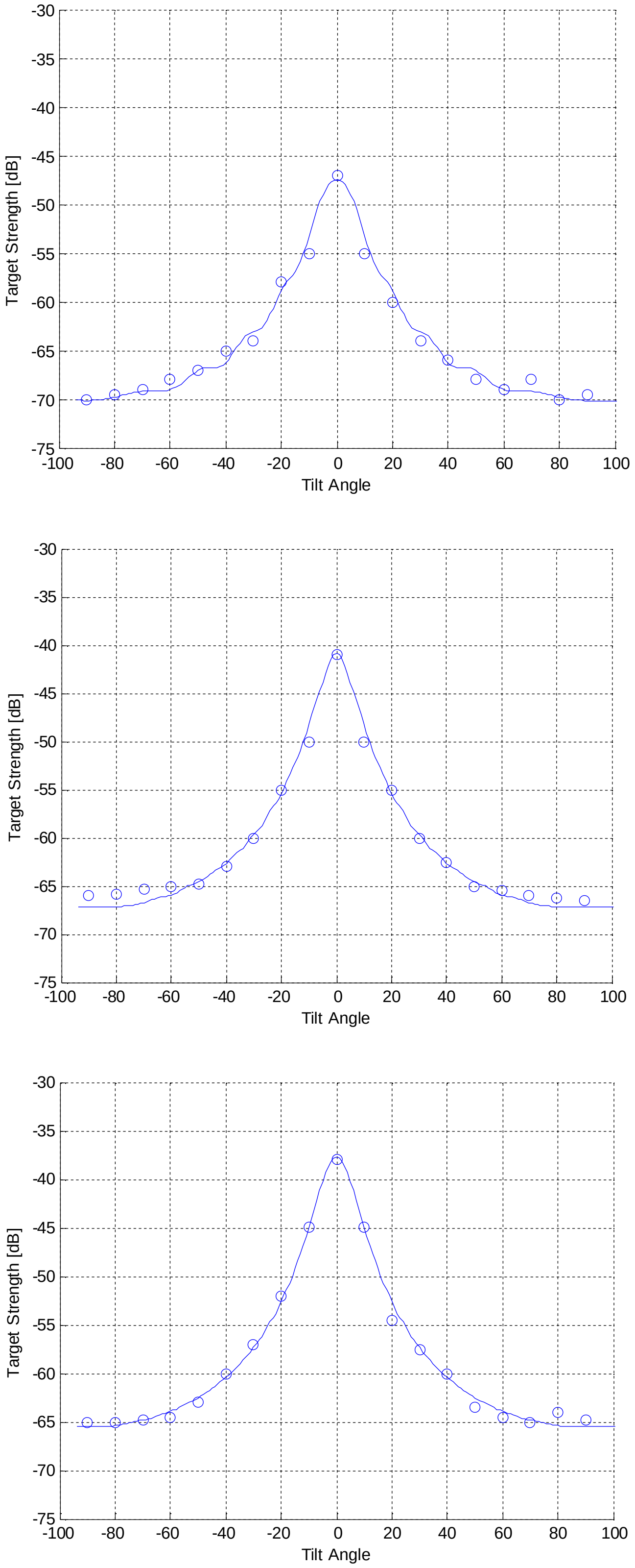

Figure 6. Measurement (o) and numerical computation (-) using 200 kHz for 10, 20, 30 cm fish length.

The dependency of sonar frequency in fish detection is shown in Figure 7. This figure shows for the fish in the same size, the increasing frequency followed by the decreasing TS value. According to Chu (2011), acoustic signals backscattered by marine animals was frequency dependent. Acoustic backscattering using multi-frequency sonar was better than a single frequency. Broadband sonar contains a continuous wide frequency band using a single transducer (Manik et al 2015). The spectral characteristics of marine organism can be obtained using broadband sonar. Application of pulse compression method increases the time domain resolution and improves the signal-to-noise ratio (Stanton 2010b).

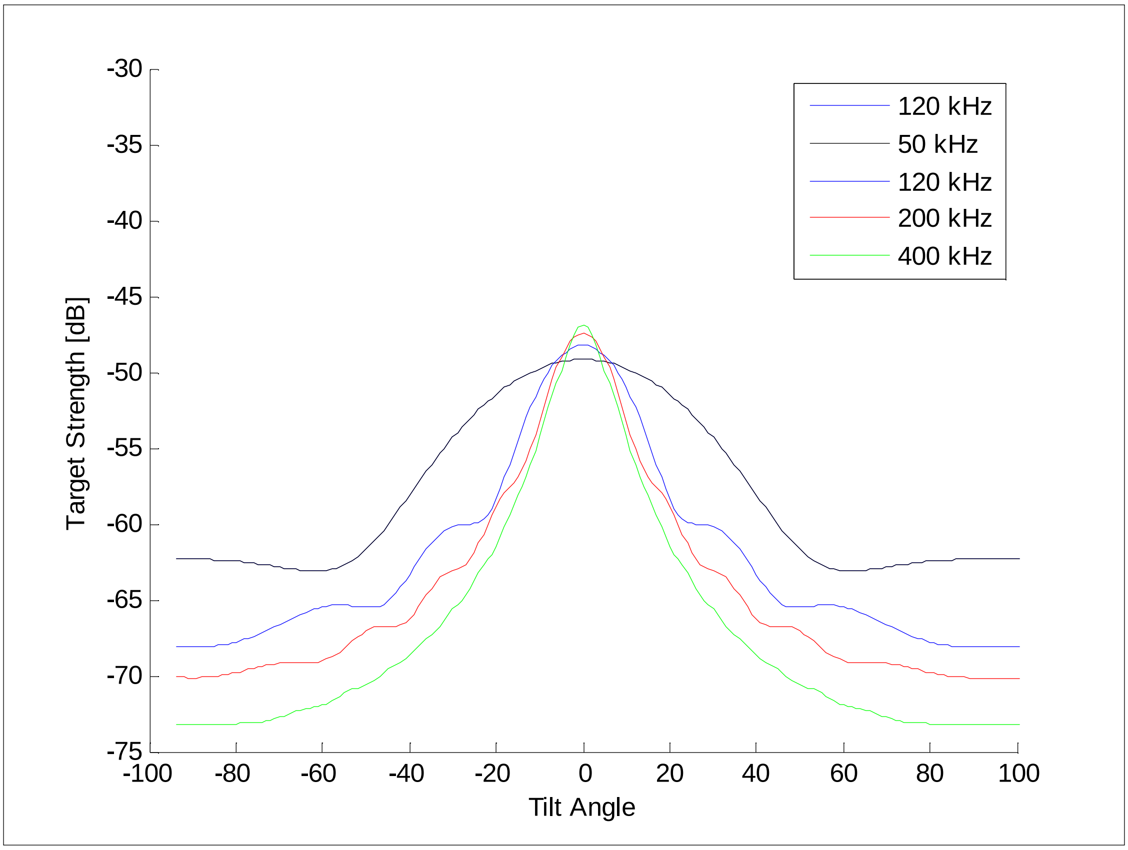

Figure 7. Frequency dependent of target strength.

Conclusions. The target strength of fish at 50 kHz and 200 kHz were measured in a water tank and compared to Prolate Spheroidal Modal Series (PSMS) model. Target strength of fish was strongly dependent on tilt angle or fish orientation to the transducer. TS maximum was found in the dorsal aspect of the fish. Sonar frequency was strongly dependent on TS measurement.

Acknowledgements. The author would like to thank Ministry of Research, Technology, and Higher Education Indonesia for supporting this research. Prof. Dr. Eng. Masahiko Furusawa is acknowledged for discussion about Prolate Spheroidal Modal Series (PSMS). The author also would like to thank the anonymous reviewers for their useful comments and suggestions to the manuscript.

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Received: 07 August 2015. Accepted: 13 September 2015. Published online: 01 October 2015.

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How to cite this article:
Manik H. M., 2015 Measurement and numerical model of fish target strength for quantitative echo sounder. AACL Bioflux 8(5):699-707.