Quantifying Fish Backscattering using SONAR Instrument and Kirchhoff Ray Mode (KRM) Model

Henry M. Manik

Department of Marine Science and Technology Faculty of Fisheries and Marine Sciences Bogor Agricultural University Kampus IPB Dramaga Bogor INDONESIA

E-mail : henrymanik@ipb.ac.id, henrymanik@yahoo.com

Abstract. Sonar instrument was used to study backscattering from tuna fish. Extraction of target strength, incidence angle, and frequency dependence of the backscattered signal for individual scatterer was important for biological information. For this purpose, acoustic measurement of fish backscatter was conducted in the laboratory. Characteristics and general trends of the target strength of fish with special reference to tuna fish were investigated by using a Kirchhoff Ray Mode (KRM) model. Backscattering strength were calculated for the KRM having typical morphological and physical parameters of actual fish. Those backscattering amplitudes were shown as frequency, body length, backscattering patterns, the density and sound speed dependences, and orientation dependence. These results were compared with experimentally measured target strength data and good agreement was found. Measurement and model showed the target strength from the fish are depend on the presence of swimbladder. Target Strength increase with increasing the frequency and fish length.

1. Introduction
Sonar instruments had long been used to detect fish in controlled condition at laboratory and free swimming at sea condition, and to estimate fish abundance or fish stocks [1]. Measurement of sound scatterers from fish are very complicated. This is due to fish size, shape, anatomy, and behavior [2]. The most significant parameters is the presence or absence of a gas-filled swimbladder [3]. All fish species reflect sound, but fish with a gas-filled swimbladder will scatter more sound than an identically sized fish without a swimbladder [4],[5]. Reflected sound from the fish with swimbladder was up to 90% from total energy backscattered [6]. The shaped of gas-filled swimbladder was an irregular and prolate spheroid. Data collected using sonar instruments are sometimes difficult to interpret. To overcome this problem, the computation of physical model combined with the measurement had been conducted in this research.

Numerical models for swimbladder were based on gas-filled spherical or prolate spheroid bubbles, and gas-filled cylinders. Helmholtz-Kirchhoff integral used to estimate backscattered sound from fish [7]. This approach was simplified by [8] who incorporated [9] finite bent cylinder equation and fluid- or gas-filled cylinders to model fish backscattering strength. Combination of these approaches to model backscatter by representing the fish body as fluid-filled cylinders that surround a set of gas-filled cylinders. They utilized finite cylinder model [10] and Kirchhoff approximations to model backscattering of fish. This Kirchhoff-ray mode (KRM) model utilizes digital morphometry of the fish.
body and swimbladder, usually obtained from CT scan images (Jech and Horne 2002). The main objective of this study is to integrate the acoustic measurement and theoretical KRM model. We used KRM model to predict backscatter along the surfaces of a fish at any orientation.

2. Methodology
The experiment was carried out in the water tank of Ocean Acoustic Laboratory, Faculty of Fisheries and Marine Sciences Bogor Agricultural University (IPB). The tank diameter is 6 m and 3.2 m deep. The end walls have wedge-shaped sound absorbers made of rubber with air cavities inside. During the period of the experiment, the tank was filled with fresh water and the water depth was 2.5 m. Figure 1 shows a diagram of the experimental setup. A single-beam transducer is mounted on the water column of the tank, looking downwards to the bed of the water tank. Transducer was operated at 200 kHz by the echo sounding system. The transducer has a radius of 18 cm and thus its 3-dB beamwidth is 6.2° at 200 kHz and sound speed of 1500 m/s in the narrow beam mode. Table 1 showed the specification and parameters of acoustic instrument to perform the laboratory measurement.

![Experimental setup in the acoustic water tank](image-url)
Table 1. Specification and parameters of acoustics instrument

| Parameters                      | Specification     |
|--------------------------------|-------------------|
| Beam type / Frequency          | Single beam / 200 kHz |
| Beam width (-3dB)              | 5.8°              |
| Pulse length                   | 0.251 ms          |
| Ping interval                  | 1.0 sec           |
| Transmitted power              | 50 W              |

Figure 2 showed the calibration sphere detected at 2.32 m depth with the target strength (TS) value was -40.1 dB. This value was suitable using the theoretical value of this sphere [11]. From the calibration result, it showed that the transmitting and receiving system performed in a good condition.

![Fig. 2. Detecting calibration sphere and water tank echo over 2500 second](image)

During the experiment, the fish was placed at 1.50 m below the transducer, and the fork length ranged from 28 to 34 cm. It means the entire fish was in the far field zone and well within the first Fresnel zone [12]. When the bar rotates, the fish was tilted relative to the beam axis, and this is equivalent to changing the incident angle of sound. The rotating system is controlled by a computer, and the tilt angle can be incremented by 1°, ranging from -90° to 90° (positive angles correspond to the head towards the source transducer).

Backscatter amplitudes were estimated using a Kirchhoff Ray Mode (KRM) model [13] parameterized for tuna fish. KRM backscatter estimates are based on digital outlines of the body and swimbladder compiled from CT-scan images. Digitized tuna fish images are rotated so that the sagittal axis of the
body is aligned with the snout and the tip of the caudal peduncle. The fish body was represented by a set of contiguous, fluid-filled cylinders surrounding a set of contiguous, wax ester cylinders representing the swimbladder. The digital resolution of the body and swimbladder was set at 1 mm. Backscatter from each cylinder in the body and the swimbladder was computed and added coherently to estimate total backscatter as a function of fish length (L, units in metres), aspect relative to the transducer face (h, units in degrees), and acoustic wavelength (k, units in metres).

Backscatter was calculated over a frequency 200 kHz and a tilt range ± 60° off horizontal. The echo intensities were calculated as reduced-scattering lengths (RSL). The nondimensional RSL is the backscattering length (Lbs) divided by the fish length (L). The usual target strength is then TS = 20 log (RSL) + 20 log (Lcm). To examine the sensitivity of the KRM-model predictions to material properties, the density (g) and sound speed (h) ratios were systematically changed as model inputs. Contrasts in sound speed (c) and density (q) are used to form reflectivity coefficients, relative to seawater (c=1490 m/s and ρ= 1031 kg/m³), at each interface within the fish (fish body c = 1535 m/s, ρ= 1050 kg m/³; swimbladder c = 1525 m/s, ρ= 903 kg/m³). Ranges of sound speeds and densities of seawater, fish bodies, and swimbladders were based on water properties during our acoustic survey and values published in [14]. Thus a total of KRM models were run at each combination of g and h for the fish body, swimbladder, and whole fish. Each 3-D fish image was vertically divided in 1 mm thick, gas-filled (representing swimbladder) or fluid-filled (representing fish body) finite cylinders. Backscatter from each cylinder was estimated using the KRM model and then coherently summed to obtain backscatter estimates for the body, swimbladder, and whole fish. A sample model of a fish body or swimbladder with normal resolution of the cylinder is 1 mm shown in Fig. 3.

Backscatter from each cylinder is estimated using a low mode cylinder solution and a Kirchhoff-ray approximation (ka > 0.2). Backscattering cross section from each finite cylinder are summed over the whole swimbladder $l_{bs}$ (swimbladder, sb) and body $l_{bs}$ (fish body, fb) and then added coherently:

$$L_{bs} = l_{bs} (sb) + l_{bs} (fb)$$

(1)

Swimbladder backscattering length $l_{bs}$ (swimbladder) is calculated from its cylindrically modeled N parts as [8]:

![Fig. 3. Ray-path reconstruction for acoustic reflection a) fish body, b) fish body and swimbladder [8].](image)
\[ l_{bs}(sb) = -j \frac{R_{fb}(1-R_{wf}^2)}{2 \sqrt{\pi}} \sum_{i=0}^{N} A_{sb} i \sqrt{k_{fb} a_{i} + 1} e^{-j(2k_{fb} a_{i} + \varphi_{sb}) \Delta l_{i}} \]  

(2)

with \( A_{sb} = \frac{k a_{i}}{(k a_{i} + 0.083)} \), \( \varphi_{sb} = \frac{k a_{i}}{k a_{i} + 40} - 1.05 \), \( R_{fs} = \frac{(Z_{sb} - Z_{fb})/\sqrt{Z_{sb} + Z_{fb}}}{(Z_{fb} - Z)/(Z_{fb} + Z)} \)

\( R_{wf} = \frac{(Z_{fb} - Z)}{(Z_{fb} + Z)} \). \( a_{i} \) are radius of cylindrical parts of fish swimbladder.

Backscattering length of fish body \( l_{bs}(fb) \) is computed as :

\[ l_{bs}(fb) = -j \frac{R_{uf}}{2 \sqrt{\pi}} \sum_{i=0}^{N-1} \sqrt{k_{uf} a_{i} \left[ e^{-j2k a_{i}} - (1 - R_{wf}^2) e^{-j(2k_{uf} a_{i} - 2k_{uf} a_{i} + \varphi_{fb}) \Delta l_{i}} \right]} \]  

(3)

with \( \varphi_{fb} = \pi k_{uf} a_{U_{i}} a_{L_{i}} (k_{uf} a_{U_{i} + 0.4}) \). The subscripts \( wf \) and \( fs \) denote the water-fish and fish-swimbladder interfaces, \( a_{U_{i}} \) and \( a_{L_{i}} \) are radius of upper and lower body parts and \( \Delta l_{i} \) is incremental distance between the elements. The amplitude \( A_{sb} \) and phase \( \varphi_{sb} \) and \( \varphi_{fb} \) are empirical adjustments for small \( ka \). The KRM model compute backscatter normalized to fish length \( L \) and called reduced scattering length \( RSL \), which is used for elongated objects :

\[ RSL = \frac{|l_{bs}|}{L} \]  

(4)

Logarithmic equivalent of the reduced scattering length is called reduced target strength and defined :

\[ RTS = 20 \log RSL = 20 \log |l_{bs}| - 20 \log L \]  

(5)

Target strength (TS) is obtained by :

\[ TS = RTS + 20 \log L \]  

(6)

3. Results and Discussion

For any digitized fish, we use the KRM model to estimate backscatter as a function of fish length, wavelength (i.e. speed of sound in water/acoustic frequency), and fish tilt. Acoustic parameter used as input for KRM model was shown in Table 2. Results from the model can be reported for the swimbladder, body, or the whole fish to show the contribution of the body parts to the total backscatter.

| Medium      | Density, \( \rho \) (kg/m\(^3\)) | Sound speed, \( c \) (m/s) | Density ratio, \( g = \rho_2/\rho_1 \) | Sound speed ratio, \( h = c_2/c_1 \) |
|-------------|---------------------------------|----------------------------|-----------------------------------|-----------------------------------|
| Sea water   | 1025                            | 1495                       | -                                 | -                                 |
| Fish flesh  | 1080                            | 1580                       | 0.969-1.068                       | 1.17-1.052                       |
| Swimbladder | 1.25                            | 355                        | 0.862-0.887                       | 1.013-1.035                      |
Figure 4 showed the dorsal x-ray images, the swimbladder is silhouetted in the body used in the KRM acoustic model. The Matlab programs were written for numerical computations of the scattering lengths and to compare the experimental result with KRM model. For two frequencies, the target strength from the “whole” fish (combining the fish body and swimbladder) is comparable to that from the swimbladder, demonstrating that gas-filled swimbladder dominates the echo. Changes in fish orientation will significantly influence backscatter amplitude and variability, which directly affects accuracy of echo amplitude to fish length (Fig. 5).

![Figure 4](image)

**Fig. 4** Fish body and swimbladder of tuna fish

The result showed that target strength from the swimbladder was higher than fish body. Figure 5 to 9 showed the comparison the acoustic measurement and KRM model. The result showed the discrepancy between measurement and model ranged from 1 to 10 dB. Both of measurement and model showed the maximum target strength at the incidence angle 0°. A fish’s beam pattern was dependent on the orientation of the fish body [15], [16]. There was good agreement between the experimental and theoretical target strengths.

The presence of swimbladder is important factor affecting the Target Strength. Swimbladder of fish provide a large acoustic impedance to flesh [17]. Acoustic backscattering by a swimbladder is 20 dB greater than the backscattering by fish bodies. Dependency of frequency changed in the magnitude of target strength for the fish are caused by swimbladder morphology and backscattering of fish body caused the oscillation. Target strength is also depend on fish length. Target strength increases with increasing fish length with correlation coefficient was 0.98 (Fig. 10).
Fig. 5. Target strength obtained by KRM model (blue line is whole fish, red line is swimbladder, green line is fish flesh)

Fig. 6. Target Strength by measurement (o) and KRM model
Fig. 7. Target Strength by measurement (o) and KRM model

Fig. 8. Target Strength by measurement (o) and KRM model
An echo is generated when the acoustic wave hit an underwater object with an acoustic impedance that is different than that of the surrounding water. The acoustic impedance depends on the material properties of the object: density, $\rho$ (kg m$^{-3}$) and the speed of sound, $c$ (m/s). The proportion of sound
backscattered at the interface of two media (e.g., water and fish body, or swimbladder and flesh) depends on the difference between the acoustic impedances of the two objects; the greater the impedance difference had the greater the backscattered amplitude. In addition to the acoustic impedance, backscatter amplitude is dependent on the size of the object relative to the acoustic wavelength ($\lambda = \frac{c}{f}$). Sound scattering can be characterized in three different ways depending on the length of the fish. If the ratio of fish length ($L$) to wavelength is less than 1, fish will reflect sound as an omnidirectional point source [17]. Sound intensity in this Rayleigh region is proportional to $L/\lambda$. As the $L/\lambda$ ratio approaches 1, sound resonates within the gas-filled swimbladder and the sound intensity is proportional to the volume of the swimbladder. When fish length exceeds the insonifying acoustic wavelength ($L/\lambda > 1$) sound reflection is specular, and is referred to as the “interference” or geometric scattering region [2]. In this scattering region, the sound intensity is proportional to the insonified surface area of the fish body or swimbladder.

The dependence of echo amplitude on aspect angle is low at low $L/\lambda$ values. As fish length or acoustic frequency increases, the influence of fish aspect on echo amplitude increases. The influence of fish orientation increases as $L/\lambda$ increases. KRM-model predictions of tuna backscatter are sensitive to changes in material properties. Changes in density or sound-speed contrasts can increase or decrease backscatter amplitudes. The resulting changes in the backscattering strength will have the greatest impact on backscatter-model predictions for species with swimbladders such as tuna. Material property measurements at appropriate pressures and temperatures are needed to refine the modeling and identification of tuna fishes. Backscatter modelling explain the target strength variability due to density and sound-speed contrasts. The combination of numerical modeling and acoustic measurements can interpret target strength and fish size more accurate.

4. Conclusions
The result of this research showed the fish backscattering was depend on orientation angle and material properties of tuna fish. Theoretical acoustic model using Kirchhoff Ray Mode (KRM) of swimbladder organism are important to explain variability in acoustic backscatter measurement, estimation fish length from target strength value, and discrimination of swimbladder and non swimbladder fish. There was good agreement between the experimental and theoretical target strengths. The implication is that the rapid variation of target strength with incidence angle is caused mainly by the irregular shape of the swimbladder.

Theoretical KRM acoustic model of fish are needed to explain the variability in backscatter measurements, to estimate fish length from target strength, and to determine the swimbladder and non swimbladder fish. Further research and modelling from acoustic backscattering signal will focus on robust methodology to compute the important biological information.

Acknowledgement
Author wish to acknowledge Indonesian Ministry of Research, Technology, and Higher Education under INSINAS Ristek Program FY 2015.

References
[1] Medwin, H and Clay, C. 1998. Fundamental of Oceanography. Blackwell Publishing Company.
[2] Chu, D., Stanton, T. K., Jech, J. M., and Reeder, D. B. 2006. Modeling of the backscattering by swimbladder-bearing fish. *Journal of the Acoustical Society of America*, Vol. 120, pp. 3105-3105.
[3] Clay, C. S. 1991. Low-resolution acoustic scattering models: fluid-filled cylinders and fish with swimbladders. The Journal of the Acoustical Society of America 89: 2168 - 2179.
[4] Weston, D. 1967. Sound propagation in the presence of bladder fish. In: Albers, V. (Ed.), Underwater Acoustics, Vol. 2, Plenum, New York, pp. 55-58.
[5] Clay, C. S. 1992. Composite ray-mode approximations for backscattered sound from gas-filled cylinders and swimbladders. The Journal of the Acoustical Society of America 92: 2173-2180.
[6] Foote, K. G. 1985. Rather-high-frequency sound scattering by swimbladdered fish. The Journal of the Acoustical Society of America 78: 688-700.
[7] Foote, K. G. and J. J. Traynor. 1988. Comparisons of walleye Pollock target strength estimates determined from in situ measurements and calculations based on swimbladder form. The Journal of the Acoustical Society of America 83: 9-17.
[8] Clay, C. S. and J. K. Horne. 1994. Acoustic models of fish: The Atlantic cod (Gadus marhua) The Journal of the Acoustical Society of America 96: 1661-1668.
[9] Stanton, T.K. 1989. Sound scattering by cylinders of finite length. III. Deformed cylinders. The Journal of the Acoustical Society of America 86: 691-705.
[10] Stanton, T. K. and Chu, D. 2008. Calibration of broadband active systems using a single standard spherical target. Journal of the Acoustical Society of America, Vol. 124, pp. 128-136.
[11] Stanton, T. K., Chu, D., Jech, J. M., and Irish, J. D. 2010. New broadband methods for resonance classification and high-resolution imagery of fish with swimbladders using a modified commercial broadband echosounder. ICES Journal of Marine Science, Vol. 67, No. 2, pp. 365-378.
[12] Stanton, T. K., Sellers, C. J., and Jech, J. M. 2010. Resonance classification of mixed assemblages of fish with swimbladders using a broadband acoustic echosounder at 1-6 kHz,” Canadian Journal of Fisheries and Aquatic Sciences.
[13] Michael Jech. 2015. Comparisons among ten models of acoustic backscattering used in aquatic ecosystem research. The Journal of Acoustical Society of America. 138 (6), December 2015.
[14] Love, R.H. 1971. Measurements of fish target strength : a review. Fish. Bull. U.S. 69:703-715.
[15] Nash, D. M., Sun, Y., and Clay, C. S. 1987. High resolution acoustic structure of fish. ICES Journal of Marine Science, Vol. 44, pp. 23-31.
[16] Reeder, D. B., Jech, J. M., and Stanton, T. K. 2004. Broadband acoustic backscatter and high-resolution morphology of fish: Measurement and modeling. Journal of the Acoustical Society of America, Vol. 116, No. 2, pp. 747-761 (2004).
[17] Reeder, D. B. and Stanton, T. K. 2004. Acoustic scattering by axisymmetric finite-length bodies: An extension of a two-dimensional conformal mapping method,” Journal of the Acoustical Society of America, Vol. 116, No. 2, pp. 729-746.