

Article

Acoustic Target Strength of the Endangered Chinese Sturgeon (*Acipenser sinensis*) by Ex Situ Measurements and Theoretical Calculations

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Abstract: The Chinese sturgeon, *Acipenser sinensis*, is a large anadromous and highly endangered protected species. The assessment of its breeding population in the Yangtze River is critically important for effective management and population preservation. Currently, hydroacoustic methods have been widely used to study the adult sturgeons in the river, whereas the acoustic target strength (TS) characteristics of the species have not been studied. In this study, the TS of Chinese sturgeon was carefully evaluated both by ex situ measurements and theoretical calculations. Six Chinese sturgeons (Body Length (BL): 74.0–92.6 cm) were measured by a 199 kHz split echosounder in a 10-m deep net cage. The computed tomography of a Chinese sturgeon (BL: 110.0 cm) was conducted and the Kirchhoff ray mode (KRM) method was used to estimate the theoretical TS. As a result, the mean ex situ TS range of the six specimens was from −26.9 to −31.4 dB, which was very close to the KRM estimation (~1 dB difference). Then, the KRM method was used to predict the TS of Chinese sturgeon as a function of BL in six frequencies commonly used in freshwater environments and to estimate the TS of a representative adult Chinese sturgeon (250 cm) as a function of frequency and tilt angle. This study can provide a good basis for future hydroacoustic studies on the critically endangered Chinese sturgeon.

Keywords: *Acipenser sinensis*; target strength (TS); acoustic backscatter; echosounder; Yangtze River

1. Introduction

The Chinese sturgeon, *Acipenser sinensis*, a large anadromous fish species, is predominantly distributed in the main stem of the Yangtze River and the continental shelf of the west Pacific [1,2]. Since the 1970s, the population of the fish has drastically declined because of habitat degeneration and overfishing [1,2]. Especially the migration route of its breeding population was completely blocked by the Gezhouba Dam (the first and lowermost dam in the Yangtze main stem) since 1981 [2,3]. In 1989, the fish was listed as one of the top-level protected animals in China, and, in 2010, the fish was

upgraded as Critically endangered (CR) species on the International Union for Conservation of Nature (IUCN) red lists [4]. Moreover, its natural spawning activity, which has been observed continually more than 30 years (at least once a year), has been interrupted (i.e., no spawning in a year) since 2013 [5]. No filial generation was produced because of the degraded breeding population which implies that the natural population of the fish is on the edge of extinction.

The Chinese sturgeon spends most of its life time at sea [1,2] (Figure 1). They mature when males are older than eight years old (approximately 150 kg and 250 cm) and females are older than 14 years old (about 250 kg and 350 cm). The adults approaching for spawning arrive at the Yangtze River estuary during June and July each year, and swim upstream along the Yangtze main stem to the spawning areas. Before the closure of the Gezhouba Dam in 1981, the spawning areas were reported in the low Jinsha and upper Yangtze River (approximately 2800 km from the Yangtze estuary) [1,6]. Two historic spawning areas had also been reported in the Pearl River [6]. Since 1981, only one regular spawning area has been reported, which is right below the Gezhouba Dam in the Yangtze River, around 7 km in total length (approximately 1700 km from the Yangtze estuary) [6,7]. Before spawning, they stay at somewhere in the middle Yangtze reach or near the spawning areas for approximately 18 months. In this period, their gonads gradually get matured. After spawning, the adults return to the sea immediately. The newly produced larvae drift along the water current and gradually arrive at the estuary, and grow up in the sea until they mature enough for spawning.

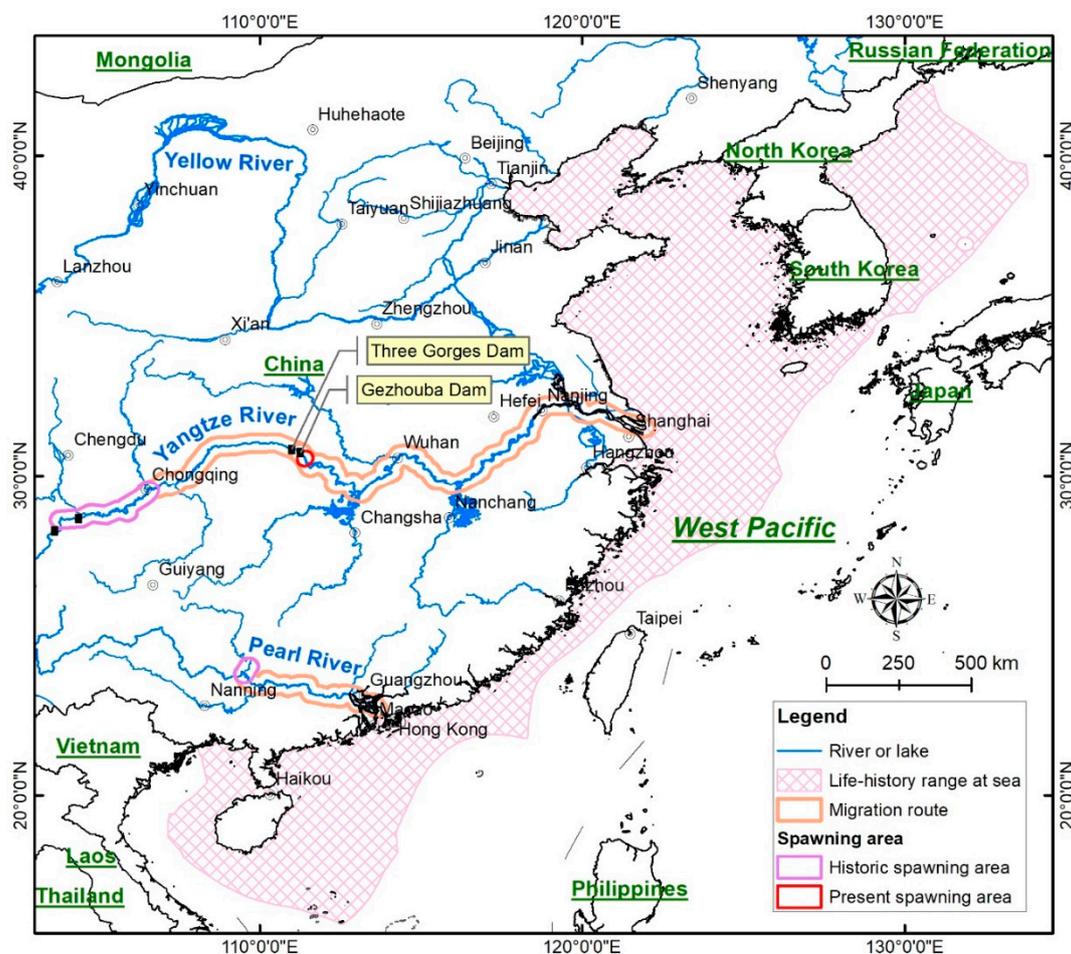


Figure 1. Life history range of the anadromous Chinese sturgeon: the species lives in the continental shelf of the west Pacific and spawns in the rivers [1,2]. Historically (i.e., before the 1980s), the spawning areas were in the upper Yangtze and Pearl rivers, however, since 1981, only one remaining spawning area has been reported below the Gezhouba Dam in the main stem of Yangtze River [6]. Geographic data were from the National Geomatics Center of China (<http://ngcc.sbsm.gov.cn>).

Globally, 27 species of sturgeons and paddlefishes belong to the Acipenseriformes order [8]. Hydroacoustics, which uses active sound in water (e.g., sonar and echosounder) to study aquatic organisms (e.g., fish) [9], has been commonly used to study the Acipenseriformes species, such as American paddlefish [10], lake sturgeon [11], white sturgeon [12,13], Atlantic sturgeon [14,15] and green sturgeon [16]. The studies mainly use side-scan sonar [11,13–15] or Dual-frequency Identification SONar (DIDSON, so-called acoustic camera) [12,16]. For Chinese sturgeon, the hydroacoustic methods have been widely used to study the spatial distribution [17,18], the abundance estimation [19–22], and spawning habitat characteristics [7,23] in the Yangtze River. Since 1997, the numbers of the adult Chinese sturgeons below the Gezhouba Dam (in about 30 km reach) were assessed by echosounder surveys and the results were issued officially [24]. However, there was no acoustic target strength (TS) study on the species up to date. The acoustic target identification of Chinese sturgeon from the echogram was done based on the assumption that the body size of an adult sturgeon was much larger than those of other Yangtze fish species. Hence, the TS of the sturgeon should be distinctively larger than those of other fishes. However, the assumption ignored the complexity of acoustic backscattering characteristics of fishes [9], and therefore might lead to some inaccurate results.

In general, the TS has been estimated using three techniques: (1) in situ measurements of free swimming in the natural habitat (i.e., in situ TS); (2) ex situ measurements of dead or live fish in a controlled environment such as a net cage (i.e., ex situ TS); and (3) theoretical or numerical backscattering models based on fish anatomy (i.e., TS model) [9,25]. The TS from a theoretical or numerical backscattering model can be examined to determine how variables such as species, body length, frequency, and orientation influence the TS values of an individual fish. For Acipenseriformes species, only the TS of American paddlefish has been estimated by an ex situ TS experiment and a Kirchhoff-ray-mode (KRM) backscatter model [10]. For the Chinese sturgeon, no acoustic TS characteristics have been studied yet.

Since 2009, fishing for the Chinese sturgeon has been banned, including for a scientific research purpose [18]. Hence, hydroacoustic methods are the only available means for studying the sturgeon in the Yangtze River. The accuracy of results such as the abundance and spatial distribution of the sturgeon using the hydroacoustic methods should be improved. In this way, the hydroacoustic methods will become more feasible and accurate to study the adult population of the fish in near future. In this study, the acoustic TS of Chinese sturgeon was estimated by the combination of the ex situ measurements and theoretical calculations. This study provides a good understanding on the TS of Chinese sturgeon to establish a better foundation for future hydroacoustic studies on the fish.

2. Materials and Methods

2.1. The Ex Situ TS Measurements

The ex situ TS measurements were conducted in a net cage base in the Three Gorges Reservoir, at the reservoir head near the Three Gorges Dam (approximately 1740 km from the Yangtze estuary). This base was specially built for culturing Chinese sturgeons. The specimens were randomly selected from the largest size group (around age 4) of fishes in the net cage base. Their length and weight were measured individually (Figure 2a) and then the specimens were put into a 5 m × 5 m × 10 m (length × width × depth) net cage (Figure 2b) for acoustic measurement. The TS of six specimens were measured one at a time. The individual specimen was freely swimming inside the net cage. A calibrated scientific echosounder system was used to conduct the acoustic measurement [9] (Table 1). The transducer was installed in a self-made buoy (Figure 2b) in the center of the net cage, and was looking down vertically with the transducer surface 0.3 m from the water surface. A laptop equipped with associated software was used to acquire and store the acoustic data (Figure 2c).

The experiments were conducted during 1–21 April 2010, and the acoustic measurements on each fish was done for approximately 24 h. The body length and weight of the six specimens used in the experiments are shown in Table 2. Note that the beam angle of the transducer was 6.8°, at 10 m

water depth, and the footprint of the beam was 119 cm, which is approximately 30–50 cm larger than the body length of test specimens (74.0–92.6 cm); however, at 5 m depth, the footprint of the beam was 59 cm, which is approximately 20–30 cm shorter than the body length of the test specimens. Therefore, the entire fish was not always ensounded, especially in relatively shallow water depths.

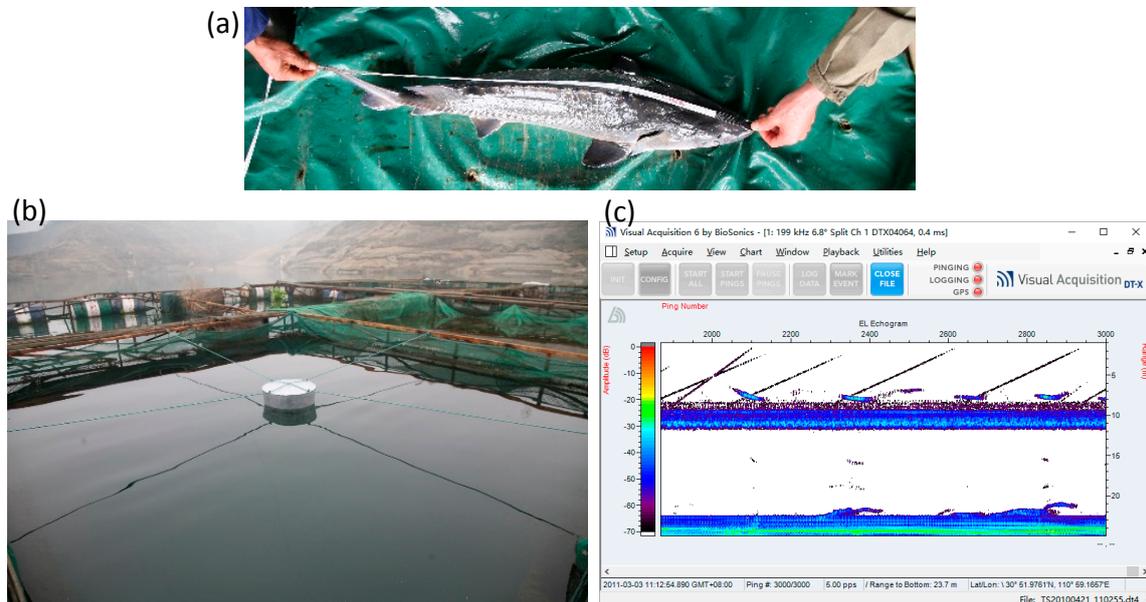


Figure 2. The ex situ TS measurements of Chinese sturgeons in a net cage base in the Yangtze River: (a) the test specimen; (b) the net cage; and (c) the echogram from the acoustic measurements by Visual acquisition 6.0.7 (BioSonics, Seattle, WA, USA).

Table 1. Instrument and parameter settings for the ex situ target strength measurements.

Item/Parameter	Value
Instrument	BioSonics DT-X split-beam echosounder (Seattle, WA, USA)
Frequency	199 kHz
Beam angle	6.8°
Source level	221 dB re μPa at 1 m
Receiver sensitivity	−51.3 dB re Counts per μPa
Water temperature	15 °C
Sound speed	1465.17 m/s
Absorption coefficient	0.01028 dB/m
Data acquisition	Visual acquisition 5.0.3 (BioSonics, Seattle, WA, USA)
Pulse duration	0.4 ms
Ping rate	5 pings per second
Collection threshold	−80 dB
Data collection range	1 to 25 m

Table 2. Six Chinese sturgeons used for conducting the ex situ target strength measurements.

ID	Total Length (cm)	Body Length (cm)	Body Weight (kg)
1	108.0	89.2	6.25
2	102.0	85.0	4.50
3	95.0	76.8	3.15
4	107.4	91.2	6.80
5	106.4	92.6	6.80
6	89.3	74.0	5.50

The acoustic data were examined and analyzed by Visual Analyzer 4.1 (BioSonics, Seattle, WA, USA) software [26]. The single traces, which could be visually identified, were selected and recognized

by using the following parameters: single echo threshold -70 dB, correlation factor 0.9, minimum and maximum pulse width from 0.75 to 3, and end point criteria -12 dB. The identified traces were exported and then imported into Excel (Microsoft, Redmond, WA, USA) to estimate the ex situ TS. The Sigmaplot 12.0 (Systat, San Jose, CA, USA) was used to plot the figures.

2.2. The Theoretical TS Calculations

The TS of zooplankton is generally modeled as fluid-filled spheres or cylinders, while that of teleost fish has been modeled using gas-filled bubbles or cylinders [9,25]. Some models replicate anatomical details of the swimbladder and body or generalize animal morphology using combinations of regular shapes such as gas-filled and fluid-filled cylinders. Simple geometric shapes used in acoustic modeling do not precisely represent fish body and swimbladder anatomy. The Kirchhoff ray mode (KRM) model was combined with backscatters by representing the fish body as a contiguous set of fluid-filled cylinders that surround a set of gas-filled cylinders representing the swimbladder [27]. The KRM method, which represents the culmination of several backscatter modeling efforts, was selected to do the theoretical calculations [25,27]. The equations on the KRM TS model can be referred in [27]. To use KRM method to calculate the theoretical TS, a cultured sub-adult Chinese sturgeon (total length 141 cm, body length 110 cm, and body weight 13.75 kg) was firstly examined using the computed tomography technology (Philips medical system, Andover, MA, USA) on 3 July 2015 in Prince of Wales Hospital, Hong Kong (Figure 3a). The fish was examined to determine the three-dimensional morphology of body and swimbladder in dorsal and lateral directions (Figure 3b, Text File S1). The KRM method was then used to calculate the TS for the fish body, swimbladder and the whole fish with the computed tomography results [27].

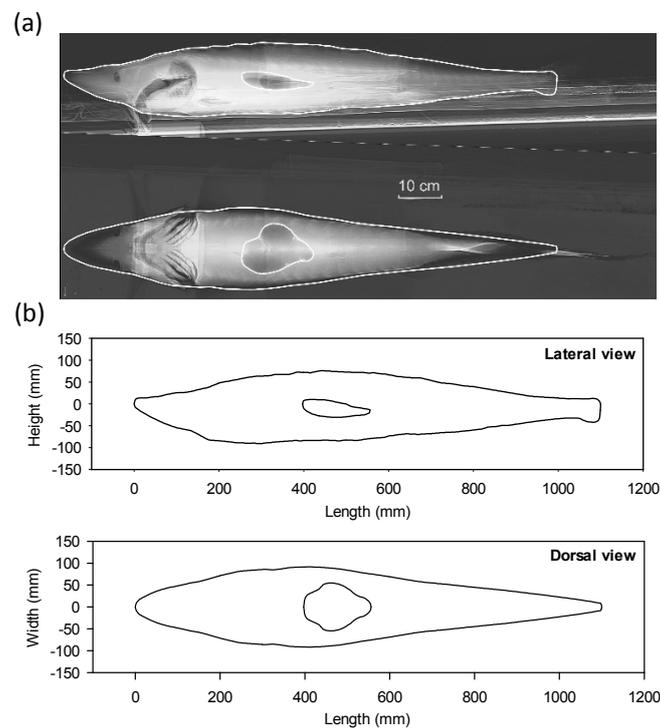


Figure 3. The body and swimbladder morphology of the examined Chinese sturgeon: (a) images by computed tomography; and (b) digitalized morphology in lateral view and dorsal view.

2.3. The Theoretical TS of Chinese Sturgeon by Body Length, Frequency, and Tilt Angle

The KRM method was further used to estimate the TS of Chinese sturgeon as a function of body length, acoustic frequency, and tilt angle. The TS as a function of the body length at six frequencies (38 kHz, 70 kHz, 120 kHz, 200 kHz, 333 kHz, and 420 kHz), which are commonly used in freshwater

environments [9,28], was calculated. To know the body length of female and male adult sturgeon, we utilized references (Table 3). Published studies reveal that the only remaining spawning area is below the Gezhouba Dam in the Yangtze River [7] where the relatively precise body size information was collected [29,30]. In general, the body length range of female adult was 212–321 cm and that of the male adult was 153–285 cm. For simplification as well as the general consideration on body length of Chinese sturgeon [31], we selected the body length of 250 cm as a representative size of the adults, and this length was further used to conduct the KRM calculations.

Table 3. Body lengths of adult Chinese sturgeons below the Gezhouba Dam in the Yangtze River.

Period	n	Female		n	Male		Reference
		Min (cm)	Max (cm)		Min (cm)	Max (cm)	
1981–2004	376	212	321	257	163	285	[29]
1998–2005	42	240	320	23	153	284	[30]

3. Results

3.1. Measured Ex Situ TS

A total of 172 tracks (water depth > 5 m) were identified for the six specimens of Chinese sturgeon (Table 4). The mean range of the distributed water depth for all specimens was 5.46–8.32 m, and the mean range of the TS was between –31.4 and –26.9 dB. Figure 4a indicates the relationship of TS and the distributed water depth for the 78 tracks of the No. 6 specimen (Table 4): the TS range was from –38.1 to –23.8 dB and the target distributed water depth was 5.11–8.97 m. No clear trend, for example TS increasing with water depth, was observed (Figure 4a). At 7 m, the TS varied from –38.0 to –26.0 dB, which implied that the body posture (i.e., tilt angle) would have a great influence on TS. Figure 4b shows the interval distribution of TS: the interval between –32.0 and –30.0 dB had 25 samples, which occupied 32.1% of the entire tracks.

Table 4. Results from the ex situ measurements and the theoretical calculations.

ID	Body Length (cm)	Number of Acoustic Targets	Mean Depth ± SD (m)	Mean TS ± SD (dB)	Min, Max TS (dB)	Model Estimation (dB)
1	89.2	9	6.21 ± 0.52	–28.6 ± 3.3	–34.1, –23.0	–29.2
2	85.0	66	6.94 ± 0.47	–27.6 ± 2.3	–32.8, –22.8	–25.8
3	76.8	11	8.32 ± 0.35	–27.5 ± 2.9	–32.0, –23.1	–27.1
4	91.2	5	7.17 ± 0.98	–26.9 ± 4.0	–32.3, –21.2	–26.7
5	92.6	3	5.46 ± 0.31	–30.3 ± 2.7	–31.9, –27.2	–29.1
6	74.0	78	6.81 ± 0.90	–31.4 ± 2.9	–38.1, –23.8	–31.6

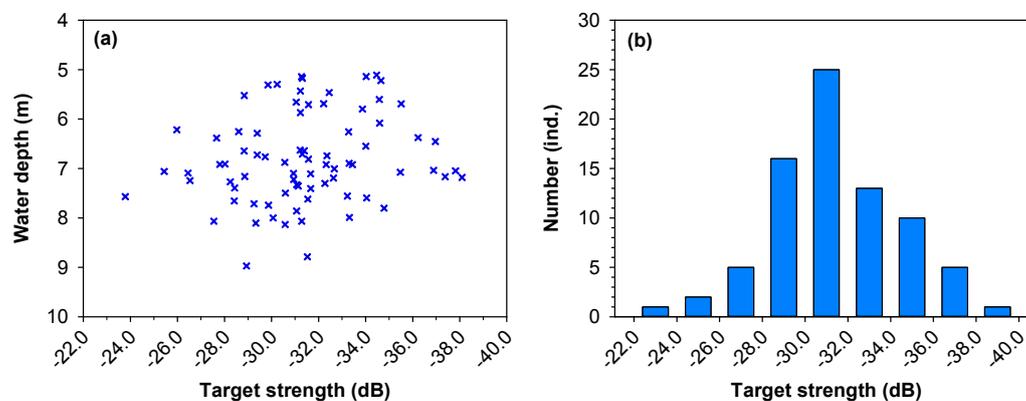


Figure 4. TS of the Chinese sturgeon (Table 4, No. 6 specimen; BL = 74.0 cm) measured in a 10 m deep net cage: (a) relationship between the TS and the distributed water depth; and (b) interval distribution of TS.

3.2. The TS Comparison of the Measurement and Model

For the same frequency (199 kHz) used at the ex situ measurements, the TS as a function of body length and tilt angle were calculated using the KRM model (Figure 5). Figure 5a shows the TS model as a function of fish length (50–100 cm) when tilt angle is 90°. The TS model fluctuated within the range of −38.2 and −25.2 dB. The six blue dots with error bars showed the ex situ TS of the six specimens. Overall, the calculated and measured TSs had a good agreement with less than 1 dB difference (Table 4). Figure 5b shows the TS model of the No. 6 specimen (Table 4, BL = 74.0 cm) as a function of tilt angle. The TS varied: its range was from −44.0 to −26.1 dB when tilt angle was between 80° and 100°. Roughly speaking, the TS range at the tilt angle (80° and 100°) is close to that of the ex situ measurements (−38.1 to −23.8 dB, i.e. 5.9 and 2.3 dB difference, respectively). In addition, when the tilt angle was 90°, which means that a fish swims horizontal, the calculated TS was −31.6 dB (Figure 5b), which was very close to the measured TS (−31.4 ± 2.9 dB), only about 0.2 dB difference (Table 4).

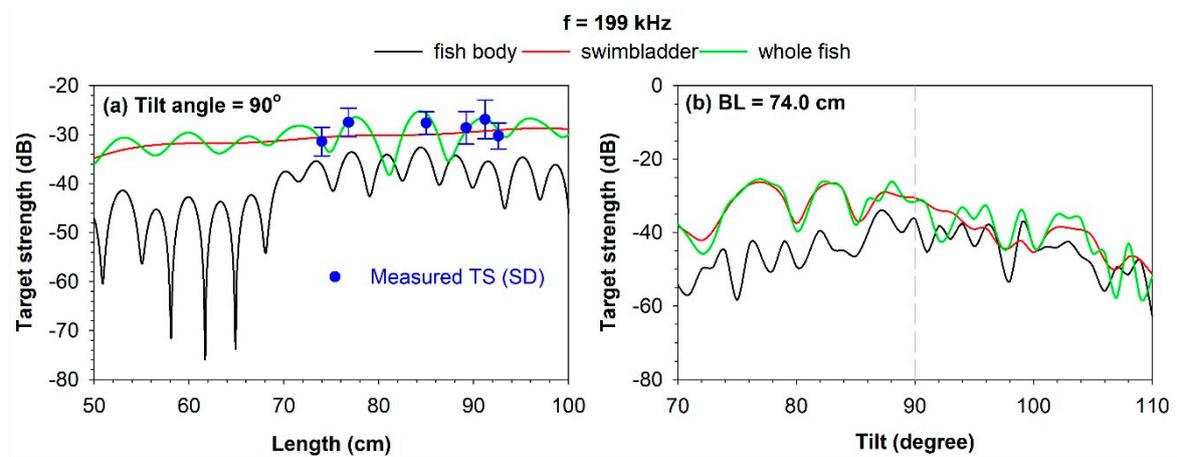


Figure 5. The comparison of measured TS and calculated TS at 199 kHz: (a) predicted TS as a function of the body length by the KRM model, where the blue dot with bar indicates the mean TS and its standard deviation of the ex situ measurement from the six specimens (Table 4); and (b) calculated TS model for the 74.0 cm specimen as a function of tilt angle (Figure 3).

3.3. TS Estimation for Chinese Sturgeons

The TS model of Chinese sturgeon was predicted as a function of body length at six frequencies (38 kHz, 70 kHz, 120 kHz, 200 kHz, 333 kHz and 420 kHz) (Figure 6). In general, the TS increased yet fluctuated with the body length at six frequencies. As the frequencies became higher, the TS fluctuated more severely. The larger the body length was, the more TS trend undulated, especially at higher frequencies (333 kHz and 420 kHz).

The TS model of an adult with representative body size (250.0 cm) was computed (Figure 7). The TS expected (from −37.7 to −14.7 dB) at frequencies from 38 kHz to 200 kHz was comparatively more stable than the TS (−42.9 to −14.2 dB) at 200–420 kHz, including several drops (down to −42.9 dB) (Figure 7a). It was clearly seen that the tilt angle had a great influence on TS (Figure 7b). The TS with the tilt angle of 70° and 90° (heading down) varied largely compared to that with the tilt angle of 90° and 110° (heading up). Figure 7c shows the TS as a function of the body length and frequency (Table S1). The three-dimensional TS surface of the swimbladder and that of the whole fish were very close each other. It indicated that the swimbladder had a dominating influence on TS.

4. Discussion

In this study, the ex situ measurements and theoretical models were combined to evaluate the TS of Chinese sturgeon. As the small beam angle, the beam could not cover the whole body of the

fish because of the shallow water depth. Figure 4 indicates that the TS did not evidently increase with the water depth. To cover the 74.0 cm specimen completely, at least 6.23 m water depth was required. Meanwhile, it is well known that most reflected energy of a fish is from the swimbladder; thus, if the swimbladder was detected, the reflected energy (i.e., TS) would be very close to that from the whole fish. A study has demonstrated that more than 90% of reflected energy of three gadoid species and mackerel is from the swimbladder [32]. In this study, only six specimens were measured because the Chinese sturgeon is one of the top-level protected animals in China. Thus, it was extremely difficult to obtain even six specimens. Furthermore, no adult was measured since very few adults were cultured in the artificial environment. They were too precious to be used for the field experiment. Hence, the ex situ TS measurement for an adult Chinese sturgeon (250 cm) was not conducted. In addition, at least ~21 m water depth would be needed to measure the whole fish, thus it is very hard to create an appropriate experimental condition in inland waters. However, the TS of Chinese sturgeon from the measurements and theoretical calculations had a high degree of agreement. It can be mentioned that the theoretical TS models based on frequency, tilt angle, and body length can be used in a future hydroacoustic work for targeting the Chinese sturgeon.

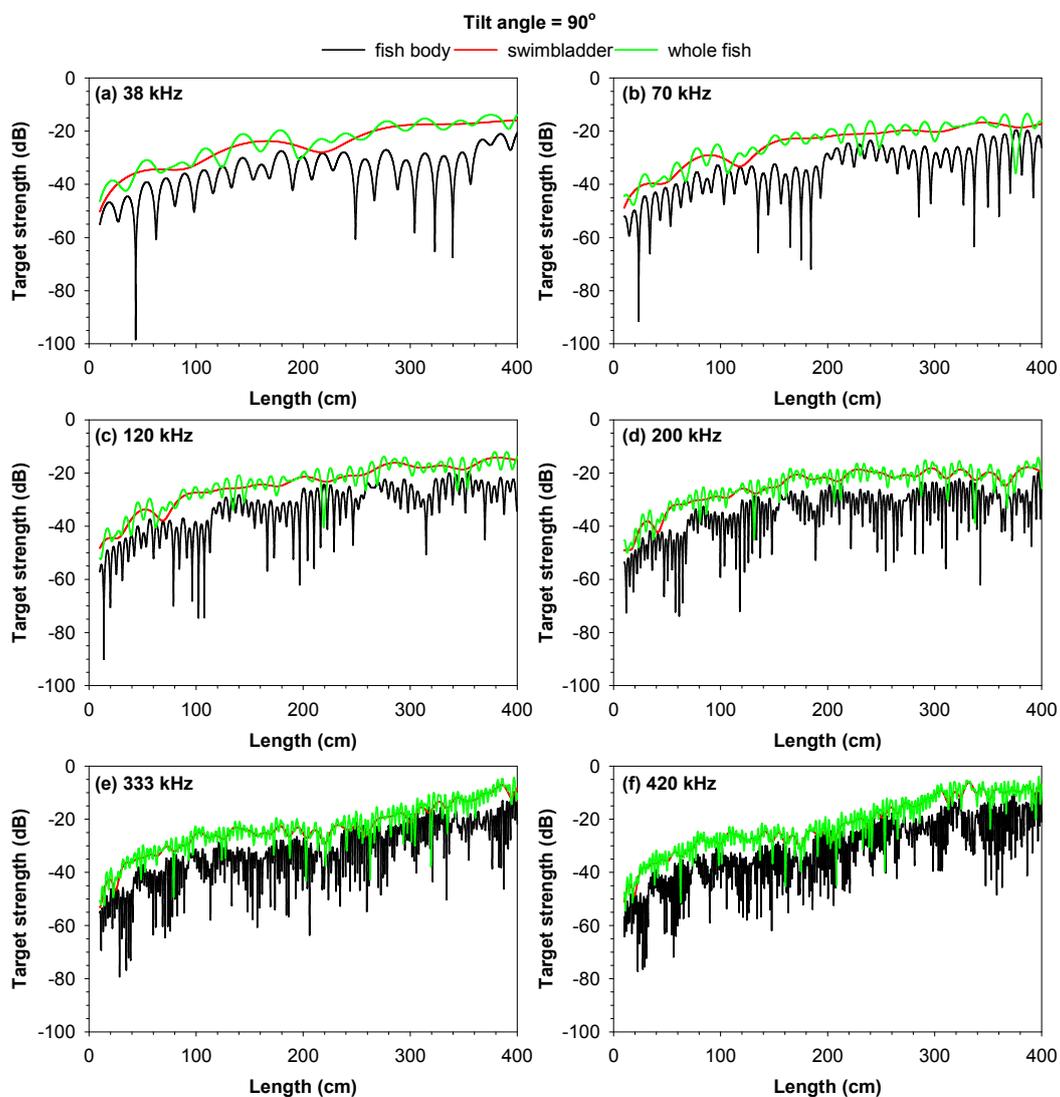


Figure 6. Estimated TS of Chinese sturgeon as a function of body lengths in six acoustic frequencies: (a) 38 kHz; (b) 70 kHz; (c) 120 kHz; (d) 200 kHz; (e) 333 kHz; and (f) 420 kHz.

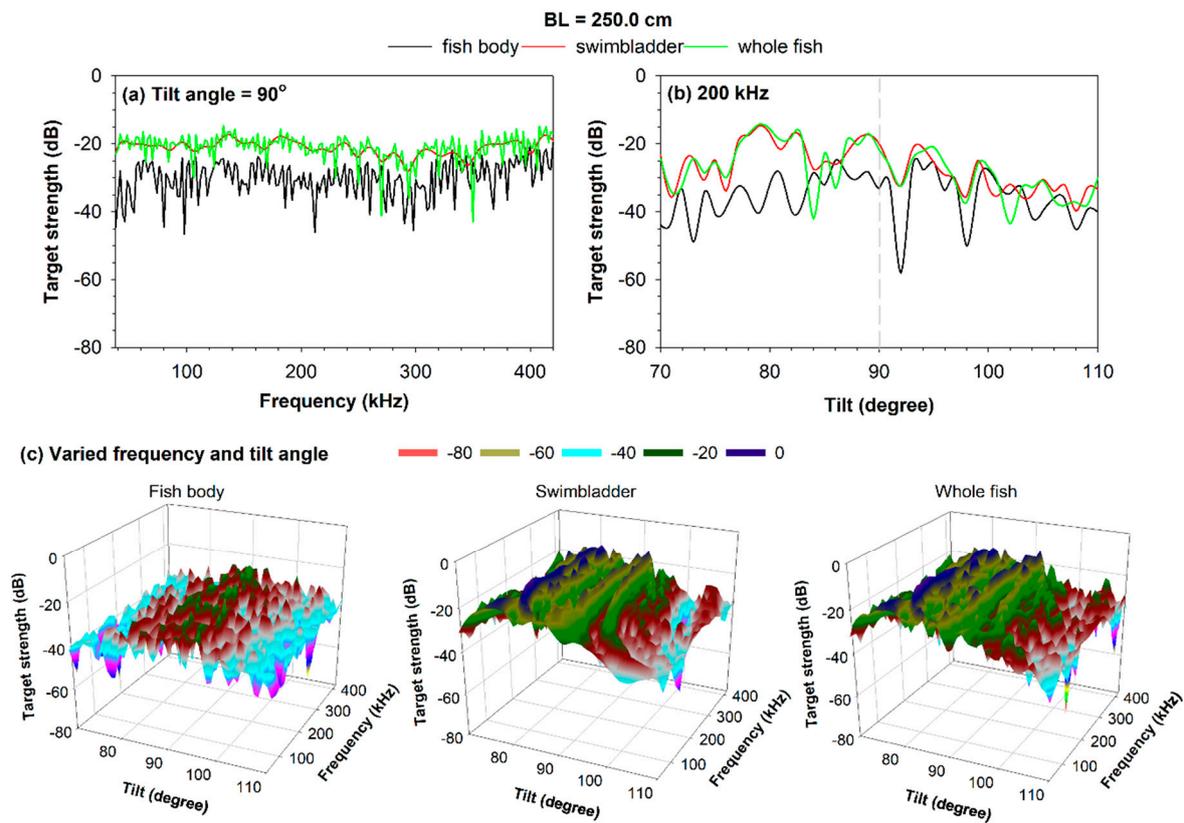


Figure 7. Expected TS model of an adult Chinese sturgeon with the representative body length of 250.0 cm: (a) TS as a function of frequency; (b) TS as a function of tilt angle; and (c) TS as a function of frequency and tilt angle.

The acoustic identification method of Chinese sturgeon from echograms should be improved. Currently, the main ground for the identification is that the adult Chinese sturgeon is large, thus its TS should be stronger than the TS values of common river fishes [17–22]. In fact, other large body fishes in the Yangtze River, such as the four major Chinese carps, can grow up to 131.1 cm in body length [33]. When the TS values of these carp species are similar to those of Chinese sturgeon, it would be terribly difficult for the Chinese sturgeon to be distinguished. Therefore, ascertaining the acoustic backscattering characteristics of not only Chinese sturgeon but also various fish species in the Yangtze River should be acquired for better fish resources management including accurate identification of the sturgeon. Furthermore, the TS was in general used to estimate the length of the target based on the traditional TS and length formula, such as Love or other empirical formulas [9,34]. The traditional empirical formulas to estimate the body length of the potential target of Chinese sturgeon need to be improved. Meanwhile, this study presented that the size and body posture of the fish had great impacts on the TS. The Chinese sturgeon with the body length of 200–400 cm could have a smaller TS than that of sturgeon shorter than 200 cm (Figure 6). For example, in 200 kHz (Figure 6d), the estimated TS for the 337.6 cm Chinese sturgeon was at a low peak value (−38.9 dB). Therefore, only TS value without consideration of tilt angle (swimming behavior) obtained from a single frequency was not enough to judge whether the echoes were from the Chinese sturgeon. In addition, the 200 kHz echosounder is the most popular frequency in freshwater environments in the world [28]. In the near future, more than one frequency on the Chinese sturgeon survey should be applied to identify the species more accurately from other species. The combination with results of the KRM model in various frequencies and those from multi-frequency survey would give a better understanding on the Chinese sturgeon.

Future hydroacoustic survey on Chinese sturgeon should be enhanced and improved. In recent years (2013, 2015, and 2017), the natural spawning activity of Chinese sturgeon was interrupted [5],

which means that the sustaining of the natural population is facing a great challenge. In the past, a number of Chinese sturgeons could be captured on special occasions such as for scientific research, and they were accidentally caught by fishermen and caught sturgeon could be used to study or estimate its population conditions in the river [35,36]. However, since 2018, the Chinese government has an ambitious plan that bans fishing for any fishes in the entire Yangtze main stem, meaning there will be no more incidental capture specimens. Therefore, only the hydroacoustic methods seem to be applicable to survey and study the adult population of Chinese sturgeon in the Yangtze River. On the other hand, future hydroacoustic surveys should not only be constructed in a zigzag mobile survey [17–22] or a stationary point survey [37], but also long-time fixed cross section monitoring is highly recommended. As the fish is a migrating species, fixed cross section monitoring in its migration route could be highly efficient with low cost [38]. In addition, new and high-end acoustic technologies [39], such as wideband and multibeam echosounders as well as omni-directional sonars and imaging sonars, all could be combined to obtain a comprehensive understanding on the fish. To improve the survey efficiency, the multibeam echosounders with large detection range could be firstly used in the 1700 km middle and lower reaches of Yangtze River to ascertain the potential distribution areas of Chinese sturgeon, then the wideband echosounder and imaging sonars/acoustic cameras [40,41] could be used to conduct more intensive surveys in these areas.

We studied the TS of Chinese sturgeon by ex situ measurements and theoretical calculations (KRM model). The results from these two methods had good agreements. We further used the KRM method to predict the TS of an adult Chinese sturgeon with the representative body length of 250.0 cm, which could be employed in the case of the hydroacoustic survey. Again, the natural population of the fish is on the edge of extinction, thus hydroacoustic methods are the only feasible means to study the wild adults. The results in this study could provide a good basis for future hydroacoustic studies on the Chinese sturgeon as well as on endangered riverine fishes in the world.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2076-3417/8/12/2554/s1>, Text File S1: 3D morphology data of a Chinese sturgeon, Table S1: Acoustic target strength of the Chinese sturgeon by KRM method.

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