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Acoustic characteristics of synthesized signals of Chinese bahaba (*Bahaba taipingensis*)

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Abstract: As a member of Sciaenidae, Chinese bahaba (*Bahaba taipingensis*) generate sounds using sonic muscles to drive the swim bladder. In this study, the drumming sounds of Chinese bahaba in two groups differing in body size were recorded in an indoor aquarium and an outdoor pond. A piecewise exponential oscillation function was developed to synthesize the signals with a good agreement. Statistical comparisons found that the oscillation frequency and damping coefficient (part 1) of synthesized signals from larger-sized fish were lower. The results suggest that the acoustic characteristics of Chinese bahaba signals are related to fish morphology as the physiological age alters. © 2021 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

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1. Introduction

Chinese bahaba (*Bahaba taipingensis*), also named the giant yellow croaker, is one of the largest of the croakers (Sciaenidae family) and has a limited geographical distribution. It can only be found in south China, from Pearl River Estuary, Hong Kong, and Macau, northwards to Yangtze Estuary. Human activities (e.g., overfishing, ocean pollution, etc.) have posed threats to their habitats, causing a significant decline in its population. Chinese bahaba has been listed as a Grade II State Protected Species in China since 1989¹ and has also been classified as Critically Endangered (CR), facing an extremely high risk of extinction in the wild, by the International Union for Conservation of Nature (IUCN Red List) since 2006.¹ Chinese bahaba has high commercial value because its swim bladder is commonly used in traditional Chinese medicine.

The members of the Sciaenidae family have been found to produce species-specific sounds for communicative purposes during reproduction, feeding, etc.^{2,3} For instance, large yellow croakers (*Pseudosciaena crocea*) generate mono-pulse signals during feeding and multi-pulse signals during reproduction.³ Whitemouth croakers (*Micropogonias furnieri*) produce disturbance calls, which consist of a burst of pulses produced at short intervals, when held in-hand.⁴ During the reproductive season, black drum (*Pogonias cromis*) produce advertisement calls in the morning and evening.^{5,6} Similar to other members of the family Sciaenidae, Chinese bahaba generate different types of sounds. Zhang *et al.*⁷ used the passive acoustic monitoring (PAM) method to collect 246 acoustic signals from 96 individuals of *B. taipingensis*. They classified the signals into seven categories (drumming sounds, humming sounds, cracking sounds, clacking sounds, birds sounds, cha goo sounds, and other sounds) based on the characteristics extracted from the spectrum. Drumming sounds are used by the males of the family Sciaenidae during courtship of the females.^{2,8,9} The typical drumming sounds have repeated pulses, called pulse-trains. Each pulse attenuates before the next pulse begins. However, according to the data reported by Zhang *et al.*,⁷ the drumming sounds of Chinese bahaba contained 1–3 pulses; most of them (139 of 175) were single pulses. Due to the rareness of this species, the information on the acoustic signal characteristics, sound production, and hearing mechanism is very limited, even though this information would be very important for the protection and conservation of this endangered species.

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Research on sound production in sciaenid fishes has been conducted in North and South America, Europe, Asia, and Australia.^{4,10,11} A previous study¹² demonstrated that the weakfish (*Cynoscion regalis*) produced sounds through swim bladder vibration caused by the sonic muscle twitch. A short pulse with two parts was generated in this process. The muscle contraction determines the oscillatory rise of the forced response, and then the pulse subsequently attenuates as the swim bladder acts as a highly damped oscillator. Many other fish species, including the Sciaenidae members, use a similar mechanism that drives swim bladder using the extrinsic sonic muscles for sound production.¹³ Chinese bahaba has a cylindrically shaped swim bladder attached by the sonic muscle. The swim bladder also has a pair of anterior horns that terminate close to the fish ear [Fig. 1(A)]. To better understand the relationship between the signal characteristics and sound production mechanism, it is important to extract the parameters from the signals and quantitatively study the oscillation and damping processes. Rosenberg¹⁴ proposed to use a piecewise function to synthesize the glottal pulse. The method well demonstrated the effect of glottal pulse shape on voice quality. In this study, we attempted to expand this method by using a piecewise exponential oscillation function to synthesize the signals based on the sound production mechanism. The oscillation frequency and damping coefficient of the synthesized signals from two fish groups were calculated and compared. The study sheds light on the relationship between the sound production mechanism and signal characteristics of this endangered species.

2. Methods

2.1 Experimental equipment and setups

PAM is a low-cost and non-invasive method to collect long term data in animal bioacoustics research.¹⁵ PAM was conducted in the Dongguan Bahaba Taipingensis Nature Reserve, Dongguan, China. Acoustic signals were recorded in a small indoor aquarium [Fig. 1(B)] and an outdoor pond [Fig. 1(C)]. The size of the indoor aquarium is $420 \times 150 \times 215$ cm, with a depth of approximately 2 m. The walls of the aquarium are made of glass, the thickness of which is around 12 mm. Two Chinese bahaba with an average weight at 22.8 ± 2.0 kg and an average full length at 125 ± 7.1 cm were kept in captivity in the aquarium (large-fish-group, G1). The outdoor pond covers an area around 6300 m^2 with a depth of around 2–2.5 m. We randomly selected 26 from 65 fish in this pond; the average weight and the average full length of these 26 fish was 10.2 ± 1.3 kg and 101.3 ± 3.7 cm, respectively (small-fish-group, G2).

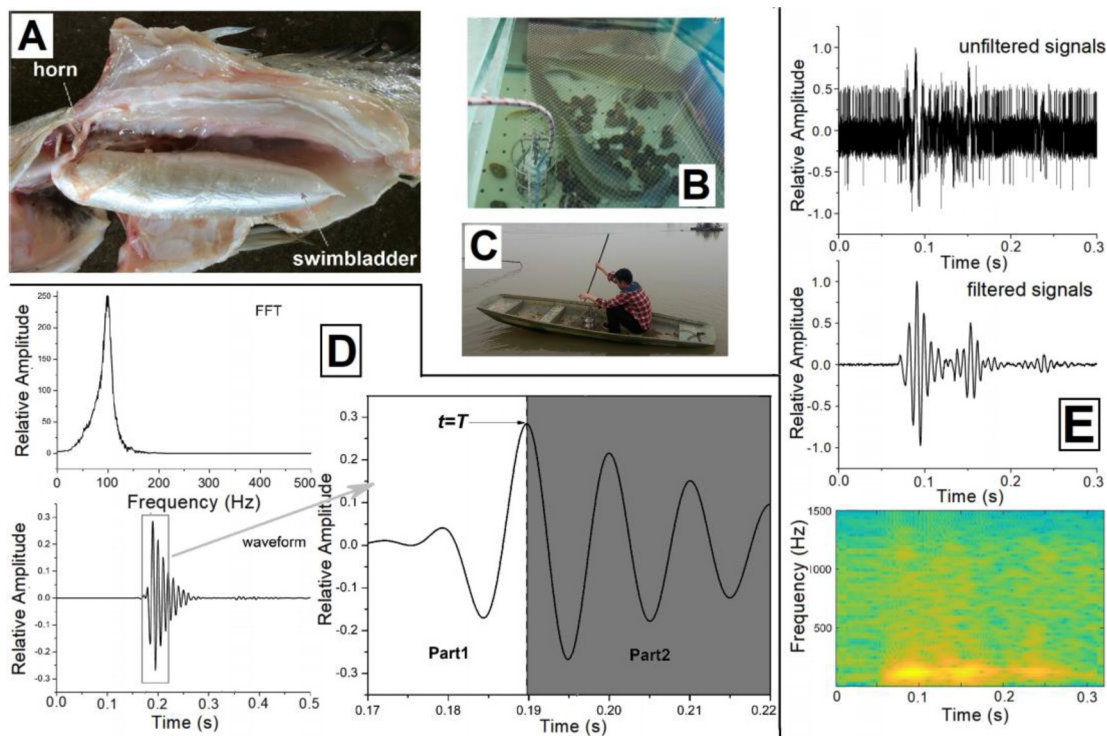


Fig. 1. (A) A photograph of the swim bladder of a wild small Chinese bahaba. (B) Passive recording in the indoor aquarium. (C) Passive recording in the outdoor pond. (D) The waveform and corresponding spectra of a typical single pulse drumming sound of the Chinese bahaba. The part of signal in the gray window is used to display the peak amplitude where the signal was separated into two parts. Part 1 is shown on a white background, and part 2 is shown on a gray background. (E) A typical drumming sound, including the waveforms of the unfiltered recorded signals and the filtered recorded signals, as well as the sonogram of the sound.

A MicroMARS hydrophone (Desert Star Systems, Marina, CA) was used for signal recording. The frequency range of the MicroMARS hydrophone is from 0.6 Hz to 33 kHz, and the receiving sensitivity range is from 70 to 166 dB re 1 V/ μ Pa. Throughout the recordings, the preamplifier was set at 18 dB. For the indoor recordings, the hydrophone was secured in the corner of the aquarium [Fig. 1(B)]. For the outdoor recordings, the hydrophone was located at the bottom of the pond, approximated at a depth of 2.5 m. The sampling frequency was set as 30 kHz for both indoor and outdoor recordings. We conducted two passive recording sessions, respectively, in the indoor aquarium and outdoor pond during the period from March to May 2017. Each session lasted for 7 days, and the collected data were saved on an SD card in the MicroMARS hydrophone. After recording, the data were exported as .wav files from the SD card and saved in the computer for later analysis.

2.2 Data analysis

Cool Edit Pro 2.1 software was used to look for the acoustic signals from the recording data. According to the frequency range of the drumming sounds produced by Chinese bahaba,⁷ we used a Butterworth low-pass filter to reduce the background noise with the frequency higher than 1000 Hz. This method could remove the higher-frequency components of the sounds; however, it is feasible, since the major energy of the sound is within 1000 Hz frequency range and the goal of this study is to fit the major waveform. Then the acoustic signals can be clearly found according to the waveform and sonogram [Figs. 1(D) and 1(E)]. We normalized the amplitude of the signals and manually extracted each signal from the recording data and saved it to a single file. MATLAB (MathWorks, Natick, MA) was then used to analyze each signal in the files. We wrote a MATLAB code to calculate the signal characteristics in both the time and frequency domains as well as using the Curve Fitting Tool (cftool) from MATLAB for fitting the curves.

A piecewise function was used by Rosenberg¹⁴ to synthesize the glottal pulse and then well demonstrated the effect of glottal pulse shape on the voice quality. To study the physical processes of oscillatory rise and oscillation damping, a similar method was developed to synthesize the acoustic signals of Chinese bahaba using a piecewise exponential oscillation function. T represents the moment when the signal reaches its peak amplitude, which was used to separate the signal into two parts (parts 1 and 2), and t is the time (s). Part 1 ($t < T$) describes the process of the oscillatory rise from the onset of the pulse to the peak amplitude [see Fig. 2(A)], and part 2 ($t \geq T$) describes the process of the oscillation damping from the peak amplitude to the end of the pulse [see Fig. 2(C)]. The piecewise exponential oscillation function can be written as

$$s = \begin{cases} A + A_1 e^{\gamma t} \cos(\omega t + \phi), & t < T, \\ A' + A'_1 e^{-\gamma' t} \cos(\omega' t + \phi'), & t \geq T, \end{cases} \quad (1)$$

where γ and γ' denote the damping coefficients of part 1 and part 2, respectively, which describe the signal amplitude reduction through time. ω and ω' are the oscillation frequencies of part 1 and part 2, respectively, which cannot be directly measured from the recording signals. ϕ and ϕ' are the initial phases of part 1 and part 2, respectively. A_1 and A'_1 represent the displacement caused by vibration at the moment $t = T$ for each part.

For each signal recorded in two groups, the nonlinear least-squares method^{16,17} was used to determine the parameters in Eq. (1) and fit the curve. The theoretical fitting function was set by a nonlinear synthesis function:

$$y'_i = f(y_i, b) \quad (i = 1, 2, \dots, N), \quad (2)$$

where $b = (\gamma, \gamma', \omega, \omega')^T$ is the undetermined coefficient vector in Eq. (2). The equation for calculating the errors e_i between the original signal parameters and the fitting function was expressed by

$$e_i = y_i - y'_i = y_i - f(y_i, b) \quad (i = 1, 2, \dots, N), \quad (3)$$

and then the objective function was established according to the principle of the nonlinear least-squares method:

$$Q = \sum_{i=1}^N e_i^2 = \sum_{i=1}^N \{y_i - f(y_i, b)\}^2 \quad (i = 1, 2, \dots, N). \quad (4)$$

To obtain the minimum value in Eq. (4), the optimal estimation $\hat{b} = (\hat{\gamma}, \hat{\gamma}', \hat{\omega}, \hat{\omega}')^T$ of the parameter b in Eq. (3) should satisfy $\partial Q / \partial b = 0$, and then the undetermined coefficient can be calculated to determine the fitting function, Eq. (2). $\partial Q / \partial b = 0$ is a nonlinear function that cannot be solved using the linear algebra method. Therefore, we used the Gauss-Newton iterative method¹⁷ to solve the function. Using this synthesized method, the oscillation frequencies and damping coefficients of 40 randomly chosen signals (20 from each group) were calculated.

Since the parameters vary from signal to signal, an analysis of variance (ANOVA) test was performed to statistically analyze the oscillation frequency and damping coefficient between two groups and to determine whether there is a significant difference between the two sets of data. A significance level of 5% was adopted for hypothesis testing ($\alpha = 0.05$) here. The previously selected 40 synthesized signals (20 from each group) were used for the ANOVA test.

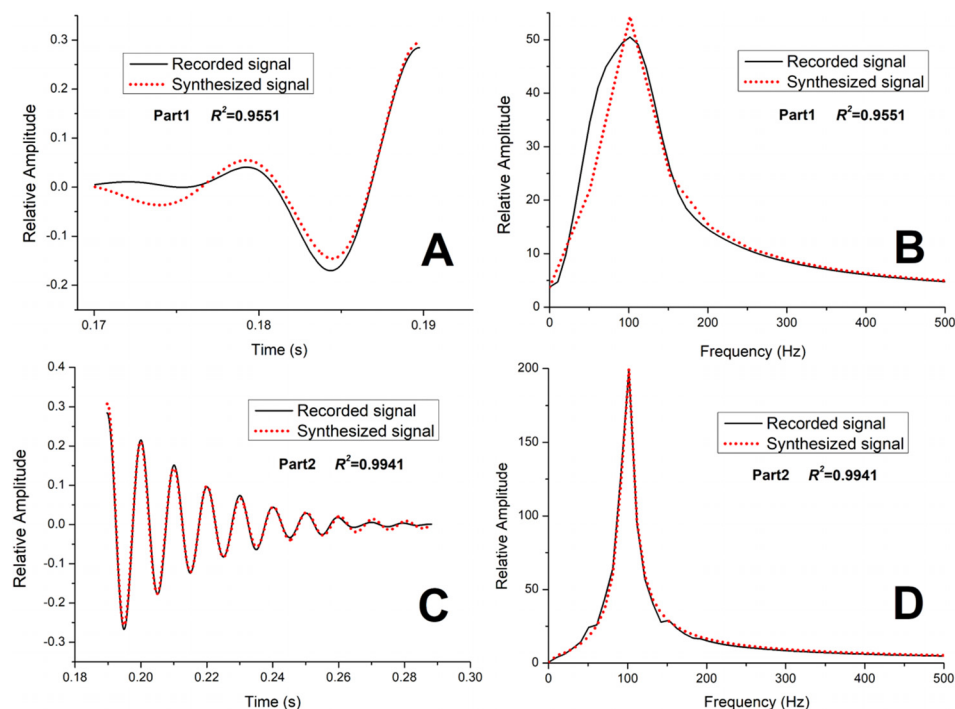


Fig. 2. Comparison of the recorded signals to the synthesized signals. The solid lines represent the record signals, and the dotted lines represent the synthesized signals. (A) The waveform of the part 1 signal. (B) The power spectrum of the part 1 signal. (C) The waveform of the part 2 signal. (D) The power spectrum of the part 2 signal.

OriginPro software (OriginLab, Northampton, MA) was used to perform the one-way ANOVA test and create the box charts.

3. Results and discussion

Figure 2 displays one of the examples of the comparison between a typical recorded Chinese bahaba signal and a synthesized signal in both the time domain and frequency domain. For the 20 signals randomly chosen from G1, the mean values of R^2 of part 1 and part 2 are 0.9712 and 0.9878, respectively. For the 20 signals randomly chosen from G2, the mean values of R^2 of part 1 and part 2 are 0.9551 and 0.9941, respectively (Table 1). The results show that the synthesized signals and recorded signals were well fitted for both parts of the signals from the two groups, indicating the parameters extracted from the synthesized signals can be used for the quantitative study on the oscillation and damping processes of sound production in Chinese bahaba.

Qualitative analysis of the signal time-frequency characteristics has been the main focus in previous work.^{3,7,18} Given this fitting method, the oscillation frequency and damping coefficient in Eq. (1) can be determined and extracted for quantitative analysis. The mean values of the oscillation frequency and damping coefficient for each part of the signals from G1 and G2 were obtained, as shown in Table 1. The amplitudes were normalized based on the maximum amplitude values of each signal. Fig. 3 statistically compared the oscillation frequencies of the signals from G1 against those of the signals from G2, as well as the damping coefficients of the signals from G1 against those of the signals from G2. For the fish in the two groups with different sizes, the oscillation frequencies of part 1 are close to those of part 2, while the damping coefficients of part 1 are distinctly higher than those of part 2 for the fish in G2. Similar to other members of Sciaenidae, sonic muscle and swim bladder play important roles in the sound production.¹³ The acoustic properties of these two organs are critical in determining the signal waveform. The process of sonic muscle twitch determines the waveform in part 1, and then the forced response and damping parameters determine the rest of the waveform in part 2.^{19,20}

For the different size fish in two groups, the larger-sized fish in G1 generate signals with average oscillation frequency as 384.3 ± 53.6 and 449.2 ± 128.4 Hz in part 1 and part 2, respectively, which both are significantly lower ($p < 0.01$, Table 2) compared to those collected from the smaller-sized fish in G2 (mean values are 588.6 ± 106 and 591.5 ± 103.1 Hz, respectively). Additionally, the average damping coefficient of the signals produced by the larger-sized fish in part 1 ($78.9 \pm 72.7 \text{ s}^{-1}$) is also significantly lower ($p < 0.01$, Table 2) than that of the signals emitted by the smaller-sized fish ($151.4 \pm 85.9 \text{ s}^{-1}$), while the average damping coefficient of the part 2 produced by the larger-sized fish is $82.7 \pm 58.4 \text{ s}^{-1}$, which is close to the parameter from the smaller-sized fish ($70.6 \pm 28.5 \text{ s}^{-1}$). The difference in the damping coefficient of part 2 between the two groups is insignificant ($p > 0.05$, Table 2). Additionally, the center

Table 1. The mean values of \bar{R}^2 , oscillation frequency $\bar{\gamma}$ (mean value \pm standard deviation), and damping coefficient $\bar{\omega}$ (mean value \pm standard deviation) were calculated from synthesized signals in each group. (Sample size for each group was $n = 20$).

	G1, large-fish-group		G2, small-fish-group	
	Part 1	Part 2	Part 1	Part 2
\bar{R}^2 (%)	97.12	98.78	96.78	97.47
$\bar{\gamma}$ (s^{-1})	78.9 ± 72.7	82.7 ± 58.4	151.4 ± 85.9	70.6 ± 28.5
$\bar{\omega}$ (Hz)	384.3 ± 53.6	449.2 ± 128.4	588.6 ± 106	591.5 ± 103.1

frequency of the recorded signals from the larger-sized fish (mean value was 66.5 Hz) was lower than those from the smaller-sized fish (mean value was 94.7 Hz). The results suggest that both neural response ability and the sonic muscle contractions might be altered as the physical size and physiological age of the fish change. Sounds are generated by driving the swim bladders with sonic muscles in many soniferous fish species.^{21,22} Chen *et al.*²³ found that the linear relationship between the weight of the swim bladder and the weight of the large yellow croakers was described by an equation, $y = 0.0146x + 0.032$, where y is the weight of the swim bladder and x is the fish body weight in large yellow croakers. As the fish grows larger (older), the larger body size comes with the longer swim bladder with the thicker wall, as well as the higher body weight. The previous data on the large yellow croakers¹⁸ showed that the older fish (with larger size) generated signals with lower frequencies compared to the younger ones (with smaller size). Previous research on weakfish²⁴ also suggested that the larger sonic muscles with longer fibers would take longer to complete a contraction; thus, the sound produced by the larger fish has a longer duration and a lower frequency. Therefore, our results of the Chinese bahaba from both the quantitative analysis based on the synthesized signals and signal processing on originally recorded data are consistent with the previous findings in both the large yellow croakers and weakfish, suggesting the signal characteristics of Sciaenidae members are closely related to the morphological changes in growth. The gas volume in the swim bladders typically is sufficient to allow the fish to approach neutral buoyancy. It not only changes with the size and age of the fish but also changes with the depth at which the fish are swimming. In our study, the depth of the indoor aquarium (G1) and the outdoor pond (G2) is 2 m and 2–2.5 m, respectively (only slightly different). Thus, the potential effects caused by the depth of the fish can be considered as limited in this study. Further work is necessary to determine how the signal characteristics change with the depth of the fish (as the gas volume in the swim bladders changes).

According to the study by Bolgan *et al.*,¹¹ sound production in sciaenid fishes has only been studied in 24 of the 298 extant species. The previous work only recorded a small fraction of these sciaenid species sounds.^{4,10} Therefore, it is critical to gain a better understanding of signal characteristics and sound production in the sciaenid species for aquaculture production, since sound plays an important role in these fishes during reproduction. Additionally, we still lack scientific information on the reproduction, habitats, and migration of the Chinese bahaba (e.g., their spawning grounds, feeding grounds, nursery grounds, etc.). Understanding the geographical distribution and migration movements of this species is a key point to the species conservation and management. However, the traditional methods for sample collection (e.g., bottom trawling) could cause environmental damage. Developing a non-invasive acoustic method, such as studying the signal characteristics, sound production, and hearing of this species, will provide fundamental information to investigate the behavior and distribution. The acoustic data will contribute toward aquaculture management and wild population protection for this endangered species in the future. The method we used in this study has a significant advantage in processing the signals collected by the low sampling rate. With lower resolution, the signal characteristics could be hard to capture.

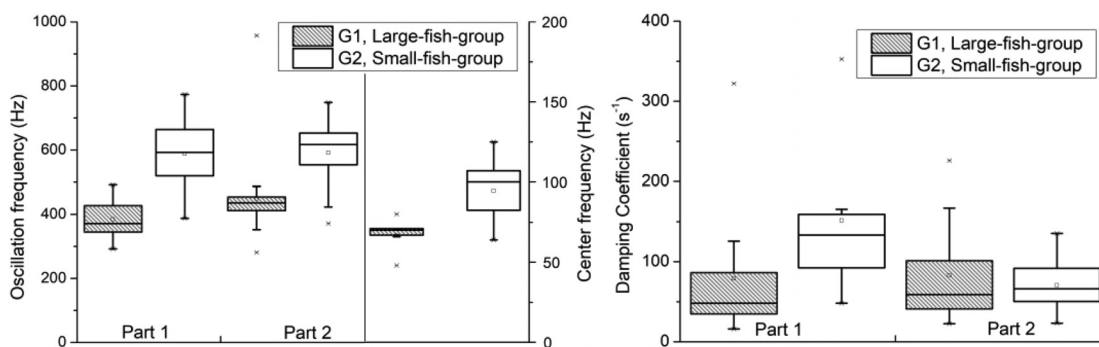


Fig. 3. Comparisons of the signals between the large-fish-group (G1) and small-fish-group (G2) in oscillation frequency and damping coefficient in each part, as well as the center frequency of the recorded signals between the two groups of fish.

Table 2. The ANOVA test results of the oscillation frequency and damping coefficient of the signals in each part between G1 and G2. (The sample size for each group was $n = 20$).

	p value of $\bar{\gamma}$		p value of $\bar{\omega}$	
	Part 1	Part 2	Part 1	Part 2
G1 vs G2	$0.00647 < 0.01$	$0.41026 > 0.05$	$2.9 \times 10^{-9} < 0.01$	$4.2 \times 10^{-4} < 0.01$
Significant	1	0	1	1

Using this synthesized method, the number of sampling points can be manually set, which can provide a significantly finer spatial resolution and allow us to capture the characteristics of the signals.

It also should be noted that our experimental conditions are limited, since the Chinese bahaba is an endangered species (Grade II State Protected Species) in China.¹ We currently do not have permission to use a large amount of fish for research. Therefore, the signals recorded in G1 were only from two fish, because we were only permitted to move two fish and feed them in the indoor aquarium. Most fish had to be kept in the outdoor pond. Also due to our limited experimental conditions, the swim bladder characteristics of fish and the physiology of the sounds have yet to be studied. We only dissected a deceased small wild Chinese bahaba years ago [Fig. 1(A)]. Unfortunately, the photographs we took did not clearly show the sonic muscles, and the swim bladder characteristics were not measured. Regarding the physiology of the sounds, they could be produced by a repeated muscle contraction (one contraction for each cycle) as in black drum, or the sounds could be produced by a single muscle contraction for each pulse as in weakfish. Addressing these questions will be important when more samples are available to us.

4. Conclusions

This work quantitatively studied the acoustic characteristics of the signals generated by two groups of Chinese bahaba fish that differ in size. A piecewise exponential oscillation function derived from speech signal processing was used to synthesize the signals. The synthesized signals closely matched the recorded signals. Based on this, the oscillation frequency and damping coefficient were extracted for statistical comparison from the signals in the two groups. The data showed that oscillation frequency (both part 1 and part 2) and damping coefficient (part 1) of the signals from the larger-sized fish were lower than those of the signals from the smaller-sized fish, suggesting that the acoustic characteristics of Chinese bahaba signals are related to fish morphology as the physiological age alters. The larger (older) fish takes longer to contract a larger sonic muscle with longer fibers, resulting in the signals with low frequencies. The results may lead to a better understanding of the sound production mechanism and signal characteristics of this endangered species. The method used in this study is a potentially promising way to determine the characteristics of the signals collected with a low sampling rate, as well as to study sound production mechanisms in other sciaenids as well as in some other fish species that produce sounds by driving their swim bladders with sonic muscles.

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References and links

- ¹M. Liu, *Bahaba taipingensis*, *The IUCN Red List of Threatened Species* (2020), e.T61334A130105307, available at <https://dx.doi.org/10.2305/IUCN.UK.2020-2.RLTS.T61334A130105307.en>.
- ²M. P. Fish and W. H. Mowbray, *Sounds of the Western North Atlantic Fishes* (Johns Hopkins, Baltimore, MD, 1970).
- ³X. Ren, D. Gao, Y. Yao, F. Yang, J. Lu, and F. Xie, "Occurrence and characteristic of sound in large yellow croaker (*Pseudosciaena crocea*)," *J. Dalian Fish. Univ.* **22**(2), 123–128 (2007).
- ⁴J. S. Tellechea, C. Martinez, M. L. Fine, and W. Norbis, "Sound production in the whitemouth croaker and relationship between fish size and disturbance call characteristics," *Environ. Biol. Fish.* **89**(2), 163–172 (2010).
- ⁵M. H. Saucier and D. M. Baltz, "Spawning site selection by spotted seatrout, *Cynoscion nebulosus*, and black drum, *Pogonias cromis*, in Louisiana," *Environ. Biol. Fish.* **36**, 257–272 (1993).

- ⁶J. S. Tellechea, W. Norbis, D. Olsson, and M. L. Fine, "Calls of the black drum (*Pogonias cromis*: Sciaenidae): Geographical differences in sound production between Northern and Southern hemisphere populations," *J. Exp. Zool. A Ecol. Genet. Physiol.* **315A**, 48–55 (2010).
- ⁷S. Zhang, L. Zhang, H. Huang, and S. Guo, "Preliminary analysis of the *Bahaba taipingensis*' acoustic spectrum characteristics," *South China Fish. Sci.* **15**(1), 1–9 (2019).
- ⁸H. K. Mok and R. G. Gilmore, "Analysis of sound production in estuarine fish aggregations of *Pogonias cromis*, *Bairdiella chrysoura*, and *Cynoscion nebulosus* (Sciaenidae)," *Bull. Inst. Zool. Acad. Sin.* **22**(2), 157–186 (1983).
- ⁹M. A. Connaughton and M. H. Taylor, "Seasonal and daily cycles in sound production associated with spawning in weakfish, *Cynoscion regalis*," *Environ. Biol. Fish.* **42**(3), 233–240 (1995).
- ¹⁰J. Ramcharitar, D. P. Gannon, and A. N. Popper, "Bioacoustics of fishes of the family Sciaenidae (croakers and drums)," *Trans. Am. Fish. Soc.* **135**, 1409–1431 (2006).
- ¹¹M. Bolgan, A. Crucianelli, C. C. Mylonas, S. Henry, J. C. Fralguière, and E. Parmentier, "Calling activity and calls' temporal features inform about fish reproductive condition and spawning in three cultured Sciaenidae species," *Aquaculture* **524**, 1–14 (2020).
- ¹²M. A. Connaughton, M. H. Taylor, and M. L. Fine, "Effects of fish size and temperature on weakfish disturbance calls: Implications for the mechanism of sound generation," *J. Exp. Biol.* **203**(9), 1503–1512 (2000).
- ¹³M. W. Sprague, "The single sonic muscle twitch model for the sound-production in the weakfish, *Cynoscion regalis*," *J. Acoust. Soc. Am.* **108**(5), 2430–2437 (2000).
- ¹⁴A. E. Rosenberg, "Effect of glottal pulse shape on the quality of natural vowels," *J. Acoust. Soc. Am.* **49**(2), 583–590 (1971).
- ¹⁵J. J. Luczkovich, D. A. Mann, and R. A. Rountree, "Passive acoustics as a tool in fisheries science," *Trans. Am. Fish. Soc.* **137**, 533–541 (2008).
- ¹⁶D. W. Marquardt, "An algorithm for least-squares estimation of nonlinear parameters," *J. Soc. Indust. Appl. Math.* **11**(2), 431–441 (1963).
- ¹⁷T. F. Coleman and Y. Li, "On the convergence of reflective Newton methods for large-scale nonlinear minimization subject to bounds," Technical Report, Cornell University, Ithaca, NY, 1992.
- ¹⁸Z. Liu, X. Xu, and L. Qin, "Sound characteristics of the Large Yellow Croaker, *Pseudosciaena crocea*," *Tech. Acoust.* **29**(6), 342–343 (2010).
- ¹⁹M. L. Fine and E. Parmentier, "Mechanisms of fish sound production," in *Sound Communication in Fishes*, edited by F. Ladich (Springer-Verlag, Vienna, 2015), pp. 77–126.
- ²⁰E. Parmentier and M. L. Fine, "Fish sound production: Insights," in *Vertebrate Sound Production and Acoustic Communication*, edited by R. A. Suthers and T. Fitch (Springer, New York, 2016), pp. 19–49.
- ²¹M. A. Connaughton, M. L. Fine, and M. H. Taylor, "The effects of seasonal hypertrophy and atrophy on fiber morphology, metabolic substrate concentration and sound characteristics of the weakfish sonic muscle," *J. Exp. Biol.* **200**, 2449–2457 (1997).
- ²²F. Ladich and M. L. Fine, "Sound-generating mechanisms in fishes: A unique diversity in vertebrates," in *Communication in Fishes*, edited by F. Ladich (Science Publishers, Enfield, NH, 2006), pp. 3–43.
- ²³H. Chen, W. Chen, G. Lin, Z. Liu, Y. Xie, and Z. Gao, "The morphological characteristics and growth pattern of cage-cultured large yellow croaker (*Pseudosciaena crocea*) in Guanjing-Yang population," *Mar. Fish.* **29**(4), 331–336 (2007).
- ²⁴M. A. Connaughton, M. L. Fine, and M. H. Taylor, "Weakfish sonic muscle: Influence of size, temperature and season," *J. Exp. Biol.* **205**, 2183–2188 (2002).