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RESEARCH PAPER

Evaluation of Fish School Resources in Shallow Sea Based on Echo Statistic Method

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Abstract

In order to obtain the spatial-temporal distribution of fish resources together with its changes in sea ranching, and realize the acoustic monitoring and evaluation of fish resource proliferation in sea ranching, the acoustic evaluation technology of fish resources based on the echo statistics method is researched in this paper. Firstly, the simulation is conducted by constructing the fish school echo signal based on the Kirchhoff-ray model, and the simulation results show that the echo statistics method is suitable for acoustic monitoring of fish stocks in sea ranching. Then, the self-developed fish finder was used to survey the national sea ranching demonstration area in the western waters of Furong Island in Shandong Province by navigating in November 2020 and March 2021 respectively. The data obtained from the two voyages were post-processed using the echo statistics method, and the density changes and activities of the fish schools in different times and regions in the surveyed sea were obtained. The analysis results show that the echo statistics method is suitable for the monitoring and evaluation of fishery resources in the sea ranching area.

Introduction

The fish stock resource assessment method can not only provide technical support to the management of sea ranching, but also can monitor the ecology of the sea areas where the fishery ecology has been destroyed (Kitada, 2020; Liu et al., 2022). Compared with the traditional trawl sampling method, the advantages of the acoustic assessment method are harmless to the biological resources, sustainable observation, and wide detection range. Till now, the most widely used acoustic evaluation technologies are the echo counting method and the echo integration method (Fabi & Sala, 2002; Nishimori et al., 2009; Ehrenberg, 1980). However, the echo counting method is only suitable for the sparse distribution of fish schools and the case that the individual fish echoes do not overlap. The echo integration method requires a priori information of the average target intensity of the individual fish (Maclennan & Simmonds, 2013; Foote, 1983). The echo statistics method is a new one for estimating fish school density by using the first-order moment and second-order moment of the echo signal. This method can make accurate estimation even though the echo signals of individual fish are overlapped, and does not require the priori information of the target intensity (Wilhelmij & Denbigh, 1984).

The study of the statistical characteristics of echo signals used to estimate the density of scatterers in water originated in 1971, the year in which Moose and

Ehrenberg (1971) proposed a second-order statistics fish school density inversion method based on the energy of the echo signal by studying the variation rule of the variance of the integrated energy of the echo signal. In 1984, Wilhelmij and Denbigh (1984) conducted a scattering experiment on a polystyrene sphere suspended in water under the action of a short acoustic pulse, and found that the second-order moment of the echo signal intensity is more sensitive to the density of scatterer. In 1991, Denbigh et al. (1991) considered the influence of beam pattern, pulse shape, and non-uniformity of the fish stock on the statistical accuracy on the basis of predecessors' work, deduced a complete echo statistical expression, and verified its validity by sea trials. In 2013, Schroth-Miller (2013) considered the impact of environmental noise on statistical accuracy and proposed a modified model suitable for low signal-to-noise ratio conditions. In 2019, LIANG (2019) developed two resource estimation methods based on broadband echo statistics by combining the advantages of narrowband echo statistics and the non-Rayleigh characteristics of fish broadband echo signals.

In this paper, the self-developed fish finder is applied to collect the fish stock data of the national sea ranching in the western seas of Furong Island by the navigating fishery resource survey method. The data is post-processed based on the echo statistical method, and the changes of fish stocks in different moments and different regions are analyzed. (Common fish species in the western waters of Furong Island include *Scomberomorus niphonius*, *Scomber japonicus*, *Larimichthys polyactis* and *Largehead hairtail*. The species parameters are shown in Table 1.)

Materials and Methods

Single fish scattering model

The single fish scattering model can simulate the echo intensity of different fish species under different conditions. In this paper, the Kirchhoff-ray model (KRM), which can approximate the morphology of the fish body and be computationally efficient, is used to construct the single fish scattering model (Stanton, 1988; Clay & Horne, 1994).

The principle of KRM is to divide the irregular fish body (or swimbladder) into a series of cylindrical slices, and calculate the backscattering cross section of the entire irregular fish (including the swim bladder) by synthesizing the backscattering cross sections of each regular cylindrical slice, as shown in Figure 1. The complete theoretical derivation process of KRM can be referred to LIANG (2019), so that won't be covered here. The KRM modeling process of a single fish can be summarized as the following:

Perform X-ray scanning of the fish, extract the upper and lower surfaces of the fish body and swim bladder contour, and build the fish body model in the coordinate system;

Calculate fish body-swimbladder, fish body-water interface reflection coefficient (Clay & Horne, 1994), incident angle of sound waves relative to fish body;

Calculate the scattering length of individual fish: $\ell=\ell_{\mathrm{fb}}+\ell_{\mathrm{sb}}$

(Where l_{fb} is the scattering length of fish body, l_{sb} is the scattering length of swimbladder)

Obtain the target strength of individual fish: $TS = 20\log|\ell|$

Fish echo signal model

Considering the actual situation of fishery resource assessment, the Poisson distribution assumption is used in fish school echo acoustic scattering modeling to describe the number of individual fish within the sonar beam irradiation range, and combined with the KRM model, the echo signals of fish school can be simulated. Assuming that the sonar emits a Continue Wave (CW) signal:

$$x(t) = a_0\cos(2\pi j f_0 t) rect(t/\tau)$$

Where a_0 is the signal amplitude, f_0 is the signal center frequency, τ is the signal pulse width, t is time and $rect(t/\tau)$ is the rectangular function.

Assuming that the number of individual fish per unit volume at time *t* is *N*, the echo of the fish

Assuming that the number of individual fish per unit volume at time *t* is *N*, the echo of the fish school per unit volume can be expressed as:

$$y(t) = a_0 \sum_{i=1}^{N} \left\{ A(l_i, \varphi_i) D^2(\theta_i) \frac{\exp(-\alpha r_i)}{r_i} \times \exp\left(2\pi j f_0 \left(t - \frac{2r_i}{c}\right) + \beta_i\right) rect\left(\frac{t - 2r_i/c}{\tau}\right) \right\}$$

Where c is the underwater sound velocity, r_i is the distance from the *i*-th fish to the sonar, β_i is the random additional phase of the scattered echo signal of the *i*-th fish, and $D^2(\theta_i)$ is the sonar directivity function value

Table 1. Main fish species and b_{20} value

	Scomberomorus niphonius	*Scomber japonicus*	*Larimichthys polyactis*	*Largehead hairtail*
b_{20}/dB	-80	-76	-68	-66.1
Ml/cm	100	64	40	-

*b_{20}: Target strength coefficient, *Ml*: Maximum length

corresponding to the position of the individual fish in the acoustic beam at time t. $\exp(-\alpha r_i)/r$ is the propagation loss term, which can be eliminated by time-varying gain compensation in the preprocessing. $A(l_i, \varphi_i)$ is the scattering amplitude, which is determined by the species of the i-th fish, its body length l_i, and the angle φ_i between the fish body and the direction of the incident wave. The relationship of the scattering amplitude $A(l_i, \varphi_i)$ and the intensity of the individual fish target can be expressed as:

$$A(l_i, \varphi_i) = 10^{TS(l_i, \varphi_i)/20}$$

The echo statistics method

According to the law of large numbers, the instantaneous amplitude of the envelope obeys the Rayleigh distribution when the number density of scattering elements is large, and deviates from the Rayleigh distribution when the number of scattering elements is small. The degree of deviation is related to the number of fish schools, and therefore can be used to predict the density distribution of fish schools.

At any time, t, the echo amplitude e_i contributed by the i-th fish can be expressed as:

$$e_i = a_i b_i c_i$$

Where a_i is the scattering amplitude determined by the scattering intensity and posture of the i-th fish itself, b_i is the acoustic beam response value of the i-th fish at that moment, and c_i is the pulse envelope amplitude of the i-th fish. Then, the signal amplitude A_N generated by N fish is:

$$A_N = \sum_{i=1}^{N} e_i \cos\theta_i + j \sum_{i=1}^{N} e_i \sin\theta_i$$

Where θ_i is the equivalent phase determined by the position of the i-th fish.
The instantaneous intensity I_N of the echo signal is defined as the square of the instantaneous amplitude of the signal:

$$I_N = |A_N|^2$$

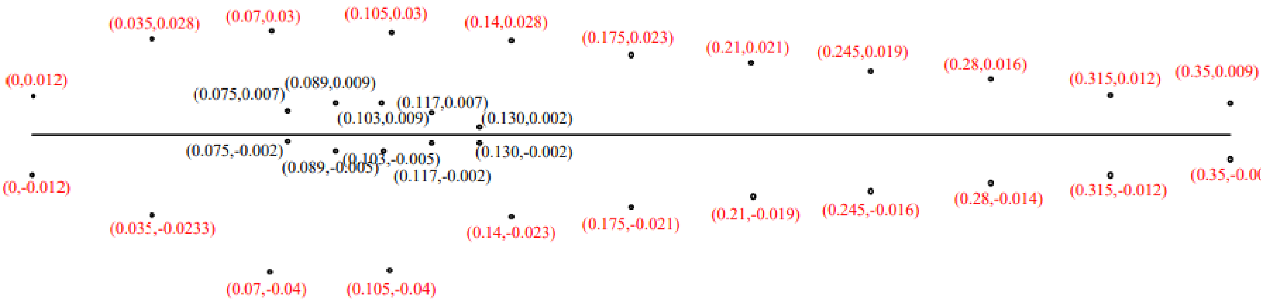

Figure 1. Schematic diagram of constructing individual fish contours (Unit: meter)

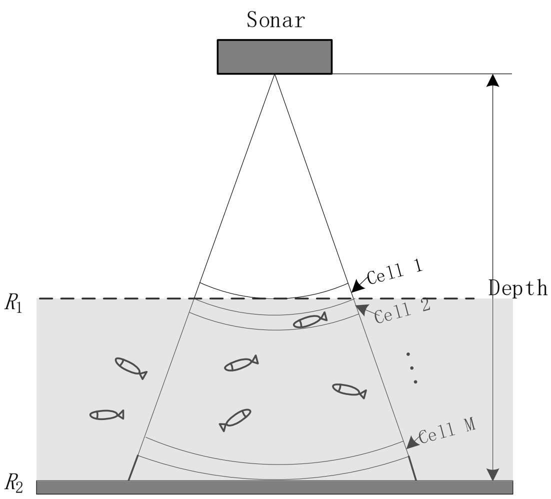

Figure 2. Schematic diagram of the micro-element division of the echo statistics method

The first-order moment $\langle I_N \rangle$ and the second-order moment $\langle I_N^2 \rangle$ of the echo signal can be obtained by polynomial derivation.

$$\langle I_N \rangle = N\langle e^2 \rangle$$
$$\langle I_N^2 \rangle = N\langle e^4 \rangle + 2\langle e^2 \rangle^2 N(N-1)$$

Assuming that the probability of fish appearing at a point obeys the Poisson distribution while the fish is swimming freely during the measurement, then the number *N* of fish in a unit area also obeys the Poisson distribution, and *N* satisfies:

$$\langle N^2 \rangle = \langle N \rangle^2 + N$$

According to above equations, the relationship among the number of fish $\langle N \rangle$ in the *j*-th infinitesimal, the first-order moment $\langle I \rangle$ and the second-order moment $\langle I^2 \rangle$ of the echo signal can be obtained.

$$\langle N_j \rangle = \frac{\langle e^4 \rangle}{\langle e^2 \rangle^2} \times \left(\frac{\langle I_j^2 \rangle}{\langle I_j \rangle^2} - 2 \right)^{-1}$$

The volume of the infinitesimal at a distance *r* from the sonar can be expressed as $\Omega r^2 c\tau/2$, where Ω is the solid angle of the beam. The density of fish in the *j*-th infinitesimal is:

$$\langle \rho \rangle = \frac{1}{\Omega r^2 c\tau/2} \times \frac{\langle e^4 \rangle}{\langle e^2 \rangle^2} \times \left(\frac{\langle I^2 \rangle}{\langle I \rangle^2} - 2 \right)^{-1}$$

Assuming that the $[R_1, R_2]$ area is divided into *M* infinitesimals, the average density of fish in the area is $\sum_{j=1}^{M} \langle \rho \rangle / M$, and the division method is shown in Figure 2.

It can be seen from the equation that the echo statistical method only needs to use the relative acoustic parameter of the echo signal, and has nothing to do with the target intensity of the individual fish. The result of $\langle I^2 \rangle / \langle I \rangle^2$ calculation has a greater impact on <*N*> when <*N*> approaches infinity, so this method is suitable for low-density fish schools.

Results

Simulation results

The simulated emission sound signal is a CW signal with a pulse width of 0.1 ms and a center frequency of 200 kHz. It is assumed that the fish body length obeys the normal distribution $N(35, 4^2)$(unit: cm), and the inclination angle of the fish body relative to the incident direction of the sound wave obeys the normal distribution $N\left(90^{\circ}, 5^{\circ 2}\right)$ (Furusawa & Amakasu, 2008). Individual fish are distributed randomly and evenly

Figure 3. Schematic diagram of binarization of individual fish X-ray scanning. (A) X-ray scan picture, (B) Binarization result.

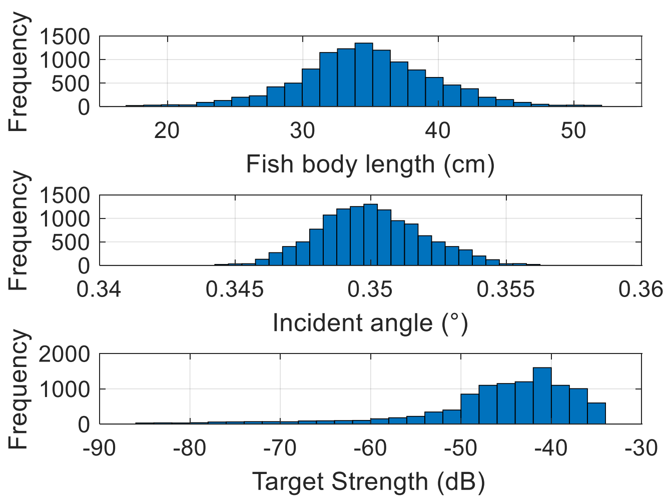

Figure 4. Target strength distribution of individual fish

within the range of 20 m ~ 27.5 m far from the sonar. The transducer is a circular piston transducer with a diameter of 14 cm and a beam solid angle of 5.5°.

The fish X-ray photos are binarized to extract the fish contour model, and then be compared with the model constructed in Clay and Horne (1994), as shown in Figure 3.

The KRM model takes the extracted fish body contour model as a reference. The body length range is 15 cm ~ 55 cm, and the sound wave incidence angle range is 0.34° ~ 0.36°. The individual fish Target Strength(TS) is counted under different parameter combinations, and the TS histogram is shown in Figure 4. It can be seen that under the given body length and incident angle

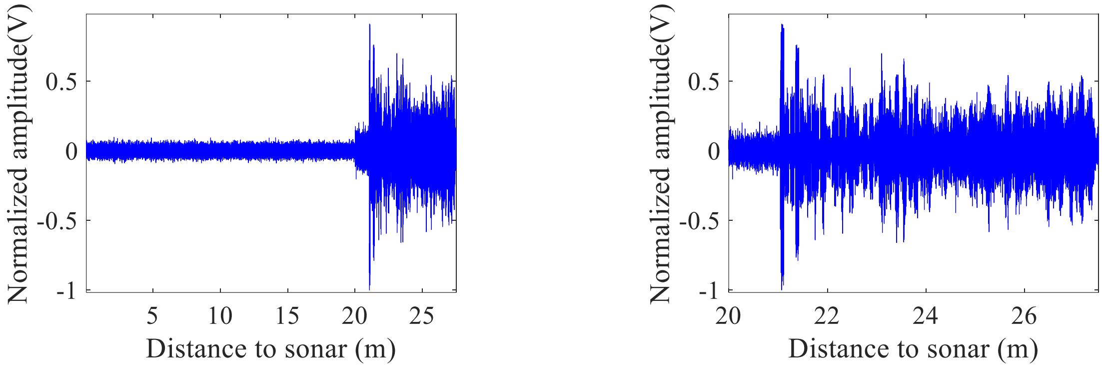

Figure 5. Signal containing fish information. (A) Overall waveform, (B) Fish wave

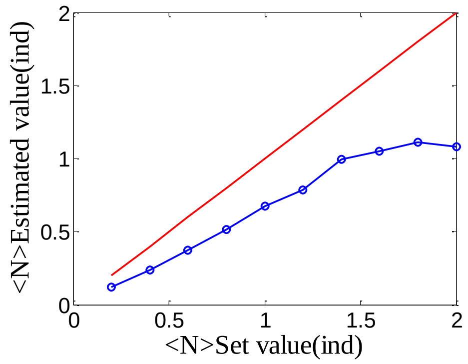

Figure 6. Corresponding relation between the set value and the evaluated value of <N>

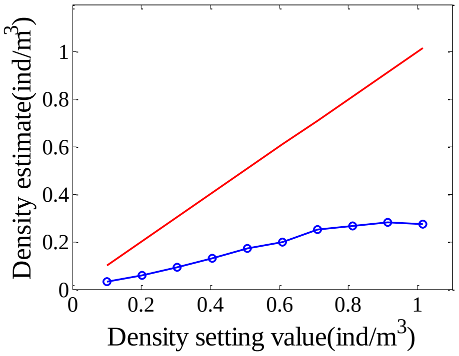

Figure 7. Corresponding relation between the set value and the estimated value of fish school density

parameters, TS is mainly distributed in the range of [-50, -35] (unit: dB).

With the known individual fish target intensity distribution, it is assumed that the average number of fish tails in each micro-element <*N*> is 2, and the signal-to-noise ratio is 30 dB. According to the formula of the fish school echo, the echo signal containing fish school information is calculated, and the typical results are shown in Figure 5.

The distribution results of the estimated value of <*N*> under the simulated signal with different <*N*> values is obtained by the echo statistics method, as shown in Figure 6. The red solid line in the Figureure is the reference line, which represents the corresponding theoretical value in different simulation settings. It can be seen that the more fish tails in the infinitesimal, the greater the deviation of the estimated value of <*N*> from the corresponding set value, that is, the larger the estimation error.

Taking into account the volume of water area where the fish layer distributes, the relationship diagram between the corresponding average density estimation value and the set value was ploted, as shown in Figure 7. It can be seen that the estimation error of the fish school density obtained by the echo statistics method gradually increases with the increase of the fish school density, indicating that the evaluation result by the echo statistics method is more accurate when the fish school density is lower. Sea ranching waters are generally shallow, irradiation range of sonar beam is limited, and there are few large-density fish schools. Accordingly, the echo statistics method is suitable for sea ranching environments.

In addition, the echo statistics method can also be used as a supplement to the echo integration method, that is, the echo statistics method is firstly used in the low-density fish school area to obtain prior information such as the target intensity of the fish, and then the obtained prior information is applied to the echo Integration method.

Sea trial results

Experimental site and equipment parameters

The project team used the navigation method to collect underwater acoustic data of the national sea ranching in the western waters of Furong Island in November 2020 and March 2021 respectively. The voyage was carried out in two days. The sea ranching area and the navigation path are shown in Figure 8. The black arrow represents the forward direction of the ship. The ship set sail at point A and ended at point J for completing the voyage. The part filled with blue is the sea ranching

A

B

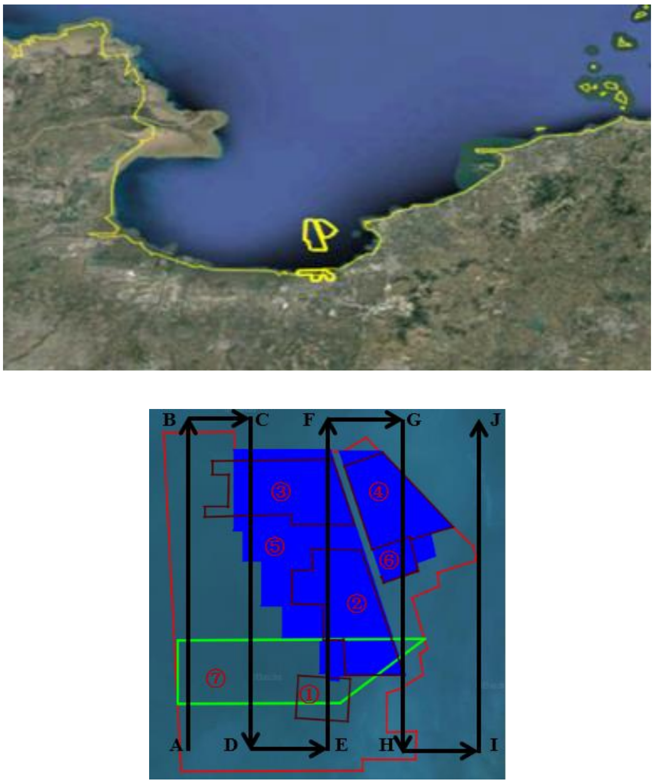

Figure 8. Schematic diagram of sea ranching area and navigation path. (A) Sea Ranching Geographical Location, (B) Sea ranching zoning and navigation path

area, where ①②③④ represents the area with artificial reefs, ⑤⑥ represents the area without artificial reefs, and ⑦ is the area with wind power.
The opening angle of the sonar device is about 10°. The transmitted signal is a CW signal with a pulse width of 1ms. The sampling frequency is 1 MHz.

Data processing results

In the process of data screening, it was found that: ①The seawater is shallow, and the seabed ground echo can be clearly seen near 9m in the vertical direction; ②The density of fish in the sea area is lower, and the effective echo detected is less.

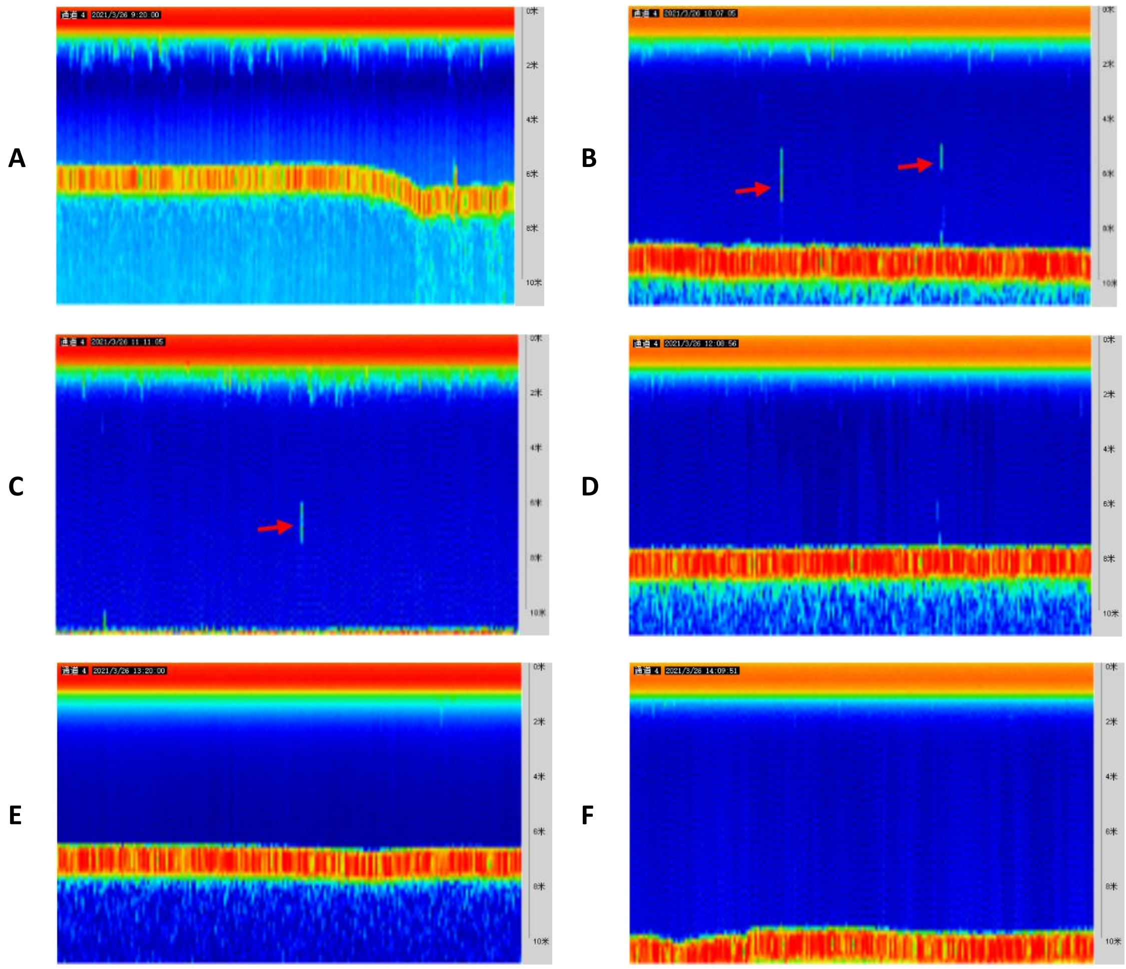

Figure 9. Acoustic images at different moments. (A) Around 9:10, (B) Around 10:10, (C) Around 11:10, (D) Around 12:10, (E) Around 13:10, (F) Around 14:10.

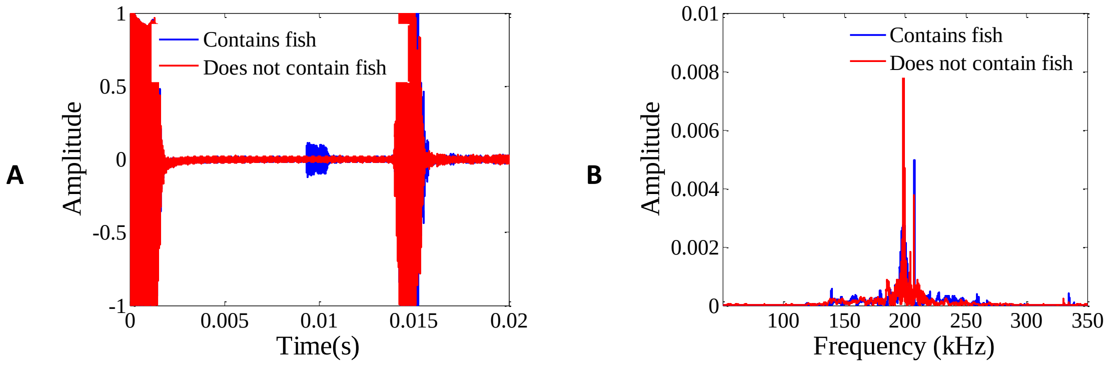

Figure 10. Typical signals with and without fish. (A) Time domain waveform, (B) Frequency domain waveform.

The signals were collected from 8:30 to 15:30 in the day. For an example, the acoustic images obtained at about 9:10, 10:10, 11:10, 12:10, 13:10 and 14:10 on March 26, 2021 are shown in Figure 9.

From the acoustic images, it can be seen that the overall density of fish schools in the sea area is relatively low, which is consistent with the fact that the number of fish schools is small due to the fast current in the nearby sea

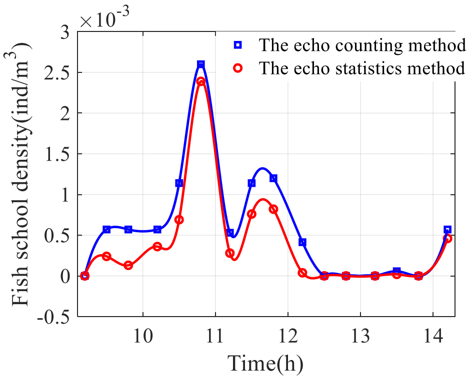

Figure11. Changes in the average density of fish schools at different times

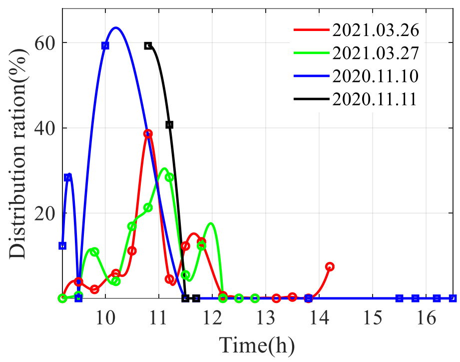

Figure 12. The proportion of the estimated target resource amount at different moments

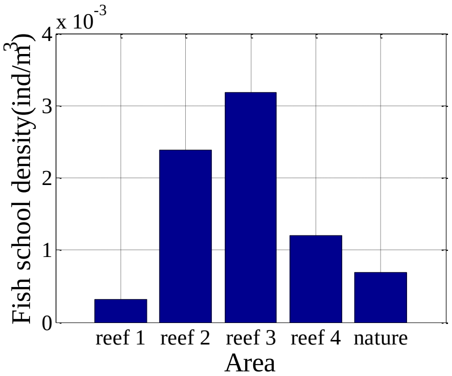

Figure 13. Changes in fish school density in different regions

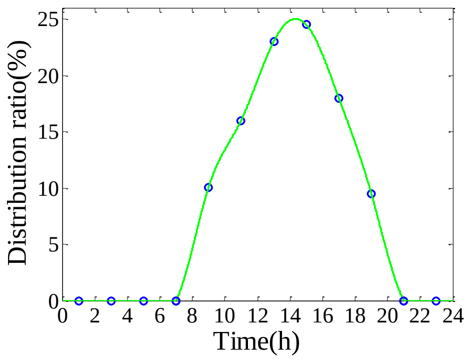

Figure 14. Density changes of fish school collected at designated locations in the Laizhou Bay

area according to the managerial staff of the sea ranching. There were obvious echoes around 10:10 and 11:10 in the morning, but no obvious echoes in other periods, indicating that the fish schools in the waters were more active in the morning. It can be seen from Figure 10 that when there are fish schools in the area, the fish echoes are more obvious and the received signal frequency does not shift significantly.

The data collected on March 26, 2021 were processed by the echo statistics method to evaluated fish stocks. The water depth of 2 m ~ 4.25 m was taken as the observation object (it is assumed that each fish layer is 0.75 m, and there are 3 layers). Every 20 minutes continuous data was processed sequentially, and then the average density changes of fish at different times were obtained. The data processing results are shown in the Figure 11.

It can be seen from Figure 11 that the evaluation results of echo statistics method and echo counting method are very close. The fish are mainly distributed in the period of 10:00-12:00, and reach the maximum around 10:40, indicating that fish activities were more frequent at this time. From 12:00 to 14:00, the number of fish was very small, and no obvious echo was observed in this monitoring experiment.

The data collected in the four working days of the two voyages were processed separately, and the target resource amount at different times is shown in Figure 12. All peaks of fish school resource density evaluated by the data of the four working days appeared between 10:00 and 11:30 in the morning, and there was almost no fish school information after 12:00, indicating that the fish schools in the sea area were more active in the morning. The corresponding peak in the autumn is earlier than that in the spring. We believe that environmental changes in different seasons have an impact on fish school activities.

The data collected on March 26, 2021 is divided into regions according to the sea ranching fish reef area setting. The evaluation results of fish resources in different regions are shown in Figure 13. The density of area ②③④ with artificial reef is higher than that without artificial reef. The area ① with artificial reef is outside the range of ocean pasture, so the fish school density is lower.

From July 27, 2019 to August 8, 2019, the project team conducted a fixed-point monitoring of the fish resources of the Sunshine Ocean Ranch in Rizhao, and the continuous 24-hour evaluation results are shown in Figure 14. Comparing with the evaluation results of Haizhou Bay in Rizhao, Shandong, it can be seen that the active time of fish school is different in different sea areas.

Discussion

In the course of the experiment, we found some problems and put forward the idea of solving the problem: ①The noise of the ship during the process of collecting data using the navigation method may have an impact on the underwater fish school, leading to the fact that estimated density is lower than the real situation. The influence of the navigation method on the evaluation results should be considered during the experiment. Small platforms such as unmanned boats can be used to improve the accuracy of the evaluation results. ②The data collection time of all voyages in this paper is around 8:30 to 14:00, which cannot reflect the activities of the fish school during the all day. In the follow-up study, 24h continuous monitoring of the pasture should be considered. ③The echo received by the sonar is affected by the attitude and position of the fish school. In the next step, the dual-frequency detection method can be considered to improve the evaluation accuracy. ④ in data processing, the echo signals of artificial reefs on the seabed should be eliminated in time to avoid its influence on the evaluation results.

Conclusion

In this paper, the echo statistics method is used to process the simulation and experimental data respectively to evaluate the fish school resources Numerical simulation results show that the greater the fish school density, the greater the fish school density estimation error, and the echo statistics method is suitable for the case of lower fish school density. After processing the experimental data, it was found that the fish schools in the Laizhou Bay Sea Ranching were more active from 10:00 to 12:00 in the morning, and the density of fish schools in the artificial reef area was higher than that in the non-artificial reef area. The echo statistics method can be used to monitor and evaluate the fishery resources in the sea ranching area.

Ethical Statement

Not applicable

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Author Contribution

Conceived and designed the experiments: Jifeng Si; Xue Li; Guoqing Ci., Performed the experiments: Jifeng Si; Yaobin Wang; Xiaoliang Xu., Analyzed the data: Yongxian Wang; Contributed reagents/materials/analys is tools: Jifeng Si; Yaobin Wang; Xiaoliang Xu.

Conflict of Interest

The author(s) declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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