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Studies on Acoustic Target Strength of Squid III. Measurement of the mean target strength of small live squid

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Abstract

Experiments to describe the squid density dependence of acoustic backscattering strength of an aggregation of encaged, free swimming squid in relation to the verification of the echo integration method, and to estimate the mean dorsal aspect target strength of relatively small-sized squid, were performed. In these experimets, various numbers of surume ika (*Todarodes pacificus*), with a mean dorsal mantle length of 16.0 cm and mean body weight of 95.1 g, were introduced into a net cage of approximately 0.64 m^3 volume.

The essential results are as follows:

(1) The echo integration method of determining squid density is valid and the phenomenon of acoustic scattering by squid under the described conditions is strictly linear.

(2) The relationships between mean volume backscattering strength $\langle SV \rangle$ and squid density ρ (squid/m^3) were $\langle SV \rangle = -51.35 + 9.85 \log \rho$ $(r=0.91)$ for 28.5 kHz, and $\langle SV \rangle = -54.60 + 11.28 \log \rho$ $(r=0.90)$ for 96.2 kHz.

(3) The estimated mean target strength were -51.35 dB for 28.5 kHz, and -54.60 dB for 96.2 kHz.

Introduction

In recent years, there has been a steadily increasing use of acoustic techniques for monitoring and quantifying fish and other marine organism stocks. Many fisheries management agencies now use acoustic systems to obtain stock-size information needed for management decisions. In nearly all applications of acoustic techniques to fisheries problems, the acoustic size of an individual fish as measured by backscattering cross section or target strength (Target strength, TS, is related to backscattering cross section, σ, by $TS = 10 \log \sigma/4\pi$) is an important parameter.

The two commonly used methods for obtaining stock-size estimates, echo counting and echo integration, both depend on the acoustic size of individual fish. The output of an echo integrator is directly proportional to the average backscattering strength of the individual fish in the population, and the effective sampling volume of an echo counting system is a function of the individual fish backscattering cross section distribution[1]. Echo counting is thus not practiced in the case of species which form dense shoals, such as squid, for which echoes from the multiple targets overlap and individual fish can not be distinguished. Consequently, the main application has been to provide information on the more widely used method

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of echo integration.

Echo integration for fish density estimation relies on the linear relationship between the integration of the received intensities or energies of echo from fish ensonified by an echo sounder and the density (number or weight per m^3) of these fish. Thus, to estimate the average density ρ, an estimate of average backscattering cross section or target strength is needed.

Basically, there are three ways of measuring the target strength of fish: first, measurement using dead, stunned, or anaesthetized specimens; second, *in situ* measurement (measuring the target strength of individual fish living free in the sea); and third, measuring the signal from a quantity of live fish enclosed in a cage which is suspended below the transducer.

This paper describes experiments on encaged live squid, one of the "bladderless fish", that is measured for the first time by this cage method. Its objectives were: (1) to describe the squid density dependence of the volume backscattering strength by aggregation of encaged, free-swimming squid in relation to the verification of the echo integration method; and (2) to measure the mean target strength of relatively small-sized squid.

Materials and Methods

1. Theoretical background

FOOTE[2,3], developed a physical model for acoustic scattering by fish aggregation. This model can be applied to the problem of acoustic scattering by an aggregation of fish if the following assumptions are made: (1) the acoustic source and receiver are essentially collocated; (2) the ensonifying signal is narrowband and of such a center frequency that the only significant multiple scattering effect is that of extinction of the incident wave; (3) the amplitude of the signal is sufficiently weak so that all nonlinear effects can be ignored; (4) the fish distribute themselves uniformly throughout a definite volume which is fixed relative to the source/receiver and in the farfield of the source/receiver; (5) the fish are identical in size; (6) the scattering parameters of a single fish can be represented by the backscattering cross section which generally is functions of the orientation of the fish.

According to the hypothesis of linearity, the acoustic echo from an aggregation of fish is merely the sum of the individual echoes. If the process of reception is linear, then the equivalent received pressure field p_{rec} is just

$$p_{rec}=\sum_{i=1}^{n} p_{rec,i} \tag{1}$$

where $p_{rec,i}$ is the component due to the i-th fish of n. In terms of the backscattering cross section σ, the product of transmitted and received beam patterns b^2, and cumulative gain G, including the reference pressure level of the source, receiver amplification, and possible time varied gain (TVG),

$$p_{rec,i}=(Gb^2\sigma)_i^{1/2}s_i \tag{2}$$

where s_i is the echo waveform, which is generally different from that of the ensonifying signal. The several factors in Equation (2) are generally implicit or explicit functions of fish orientation and position in the beams of the acoustic source and receiver, as well as the physical state of the fish.

The instantaneous intensity, I, corresponding to p_{rec} is

$$I=(\rho c)^{-1}p_{rec}^{2} \quad (3)$$

wher ρ and c are the density and sound speed of the medium, respectively. The product ρc is constant factor for the assumed acoustically homogeneous region of the fish aggregation.

The energy of the received echo, is the time integral of the instantaneous intensity, or

$$E=\int_{0}^{\infty} I(t)dt=(\rho c)^{-1}\int_{0}^{\infty} p_{rec}^{2}(t)dt \quad (4)$$

where the integral, in practical case, is taken over the duration of the received echo signal. It is necessary to remember that the echo energy E is same whether expressed in the frequency domain or time domain, does not depend upon the system phase resonance, although the pulse shape does, and the latter can be radically different, especially near the minima in the orientation distribution of fish in the sound beam.

It is convenient for the study of E in this equation to invoke the random phase approximation and the ergodic hypothesis. For the present purpose, the random phase approximation assumes the additivity of the energy in individual fish echoes. The ergodic hypothesis equates the long-term time average of a quantity such as the effective acoustic backscatering cross section of a single or identical fish with the ensemble average of the same quantity.

In this context, an expression for the energy as the mean of a sufficiently large number of independent ensonifications of the fish aggregation and in the absence of noise, can be written,

$$\langle E\rangle=c_1\rho\langle\sigma\rangle, \quad (5)$$

where c_1 is a system parameter determined using standard calibration techniques, ρ is the average density of fish detected per ping, and $\langle\sigma\rangle$ is the average backscattering cross section of fish. In its general form, $\langle\sigma\rangle$ can be expressed by

$$\langle\sigma\rangle=\int Gb^2\sigma dF \Big/ \int Gb^2 dF, \quad (6)$$

where dF is the probability element associated with squid position k, orientation distribution K, length l, and other possible variable characteristic x of fish in the aggregation, such as species, condition when observed acoustically, and behaviour insofar as social interactions may influence the fish as acoustic scatterers. This averaging models of backsacttering cross section have been examined in the previous study[4] and are beyond the scope of this paper.

In logarithm form, Equation (5) can be simplified as

$$\langle SV\rangle=10\log\rho+\langle TS\rangle. \quad (7)$$

This is the basic equation for the estimation of fish density ρ by the echo integration method and was applied in the present study for the estimation of the mean target strength of relatively small live squid.

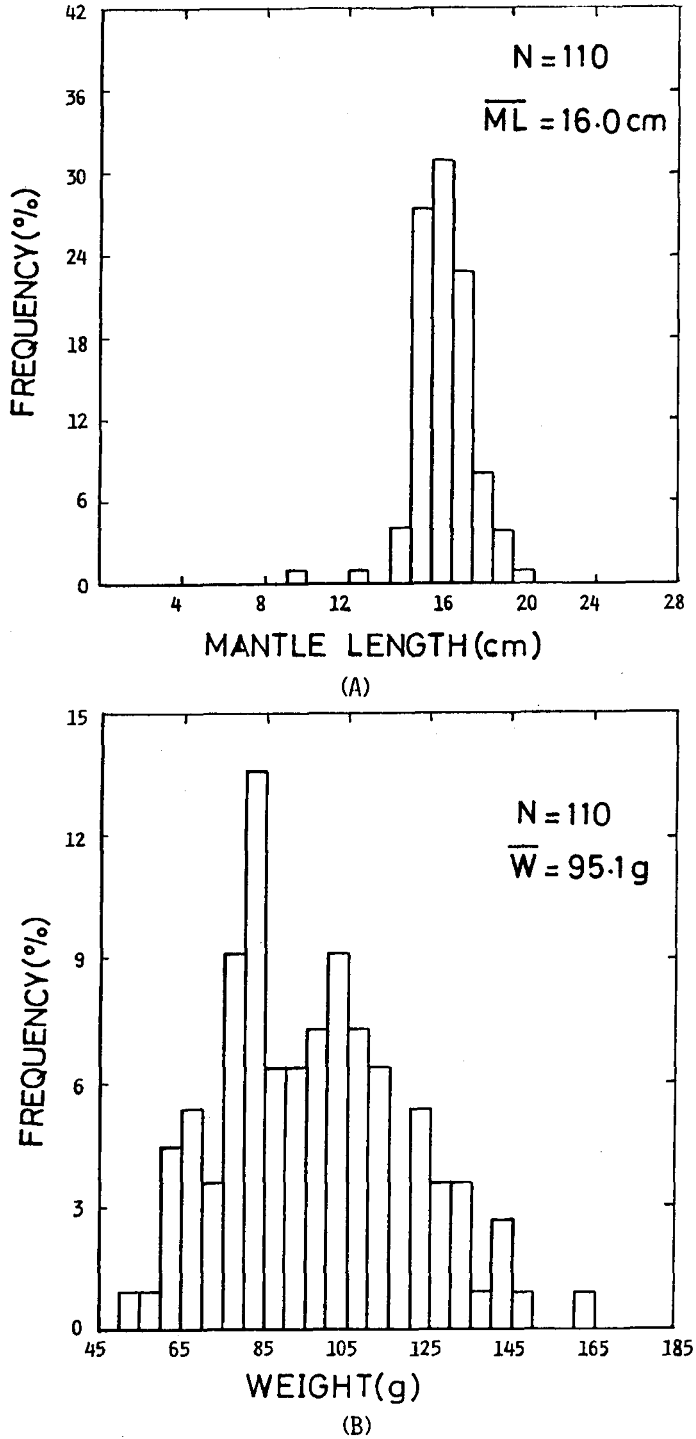


Fig. 1. Frequency distributions of dorsal mantle length(A) and body weight(B) compositions of surume ika (*Todarodes pacificus*) used in measurements.

2. Materials

The good supply of living squid was ensured by the local abundant/populations of squid, caught by fisherman using automatic squid jigging. Surume ika (*Todarodes pacificus*) was the subject of the measurements because of their abundance at the time of the experiments (June-July, 1988), and the fact that until now there has been no data on this live squid's target strength.

The number of squids used for measurements were 110; dorsal mantle length and body weight histograms are presented in Fig. 1. The mean mantle length and body weight were 16.0 cm and 95.1 g, respectively.

3. Experimental set-up

The measurements were performed from a specially designed platform at Usujiri fishing port, Minami Kayabe, Hokkaido. The average water depth was 7.5 m, and

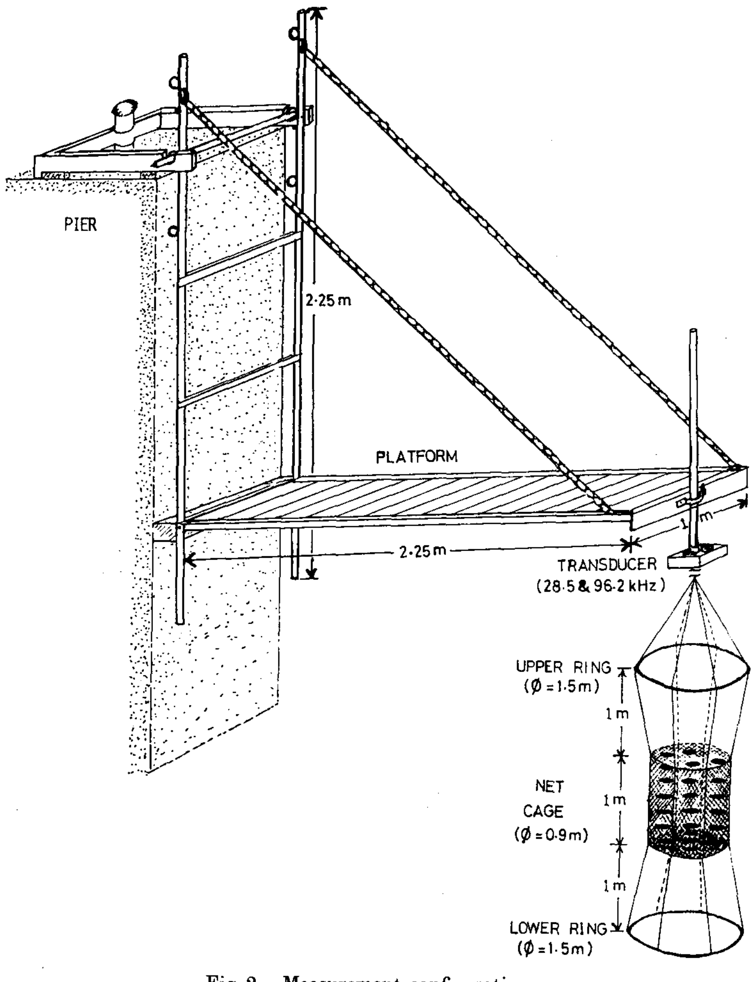


Fig. 2. Measurement configuration.

the typical tide range of 0.75 m produced no measurable underwater currents near the experimental site. Boats entered this experimental site only occasionally and the experiment was stopped in those instances.

The experimental setup is shown in Fig. 2. During measurements, the net cage was suspended on a monofilament line on the acoustic axis with its center at the position of the calibration sphere (standard steel ball of diameter of 41 mm) at a depth of 6 m. The net cage was designed similarly to those of ROTTINGEN's study[5]. The height and diameter of the nearly cylindrical volume defined by the net cage were 1.0 m and 0.9 m, respectively, with a volume of approximately 0.64 m^3. The material of this cage was knotted polyethylene netting, with a filament diameter of 0.3 mm and mesh size of 10 mm, *i.e.*, nearly acoustically transparent material. The upper and lower metal suspension rings, each of diameter 1.50 m, were placed at 1 m distance from the net cage ; thus the echoes from these rings were not included in the integration. In order to reduce the effect of unwanted objects in the water (including a large number of jellyfish), a specially contructed net fence 4 m by 4 m and 8 m depth, was set outside the net cage at the experimental site during measurements.

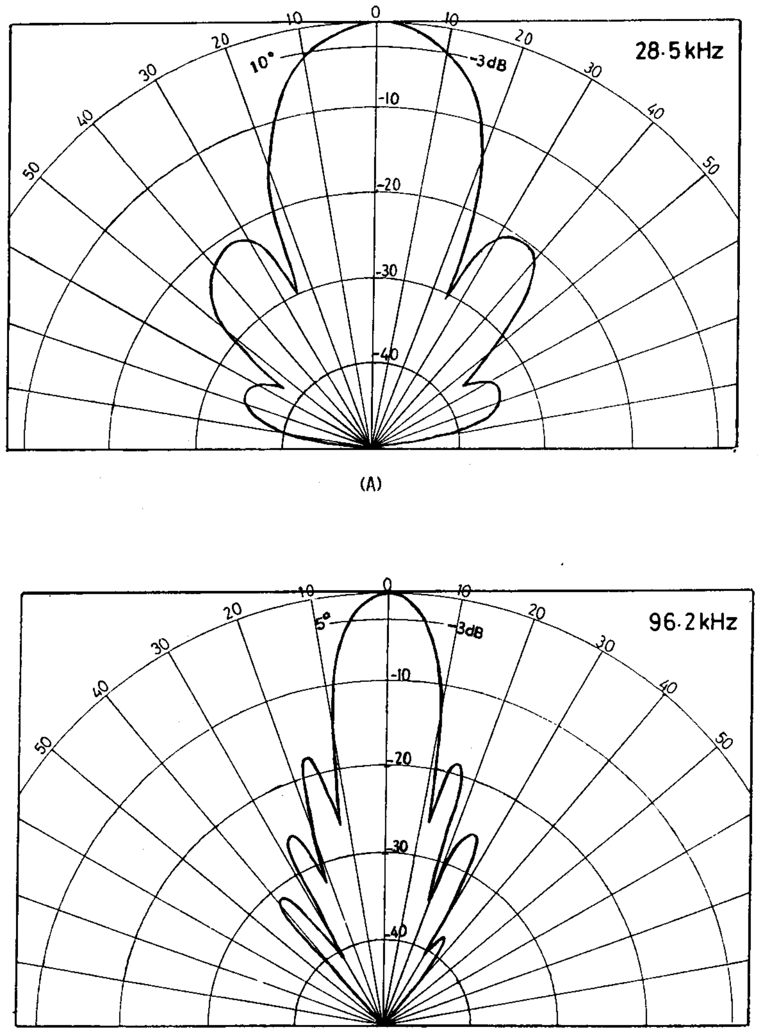
All acoustic (squid) measurements were performed relative to the reference target. Measurements of this reference target and empty net cage were conducted before squid measurements. Also, preliminary measurement for one squid was conducted to facilitate the comparison of the histogram of peak amplitude with the main measurements, *i.e.*, from a density of 50 to 173 squids/m^3. Before an acoustic measurement was made, the net cage was hoisted to the water surface, and the desired amount of squid was transfered through an opening on the top of the net cage. Then the net cage was lowered to the desired depth.

The acoustic equipment consisted of a KAIJO DENKI SR-43 echo sounder, which had two transducers of 28.5 kHz and 96.2 kHz, respectively, and the same pulse duration of 0.5 ms. Each of the two transducers had a beamwidth of 10.0 deg and 5.0 deg for 28.5 kHz and 96.2 kHz, respectively. The directivity pattern of these transducers are shown in Fig. 3. Some of the associated electronic equipment that is not described in Fig. 2 above, included a four channel Data Recorder (TEAC R-200) and three channel Oscilloscope (KIKUSUI COM 7101A), for continual monitoring of signals under recording on data recorder.

During measurements in the field, the signal at the output of the echo sounder's receiver was then stored in analogue form on the magnetic tape of the data recorder. Each complete measurement involved the recording of approximately 500 successive pings from a given density and ensonifying frequency. The recorded data were analyzed later at the laboratory.

4. Data processing

The two channels of a FFT Analyzer (ONO SOKKI CF-920) were used to compute the echo energy from the reference target, empty net cage, and encaged squid aggregations. At first, the magnetic tape was played back and the echo signals then inputted into the FFT Analyzer. In this FFT Analyzer the 12 bit A/D Converter automatically converted the signals from analogue form to digital form by the 51.2 kHz sampling frequency, or along a display time scale of 8 ms with 0.0078 ms sampling interval. In the second operation, the digitized echo signal was



(A)

(B)

Fig. 3. Directivity pattern of 28.5 kHz(A) and 96.2 kHz(B) transducers.

squared and time integrated for each of a sequence of 500 pings. The mean echo energy for each squid density and ensonifying frequency was obtained by averaging all of the 500 echo energies by personal computer (NEC PC-9801 vm2). To show the variation of the peak amplitude for the 500 pings of the echo signal with respect to the squid behaviour in the net cage, histograms were also made with additional analysis by the theoretical (Rayleigh) PDF and Generalized Gamma PDF[6].

In the analysis of the encaged squid aggregation series, the measured average echo energy due to the empty net cage and reverberation were substracted from the computed means. The next operation was to compute the mean volume backscattering strength from the measured and computed mean echo energy by

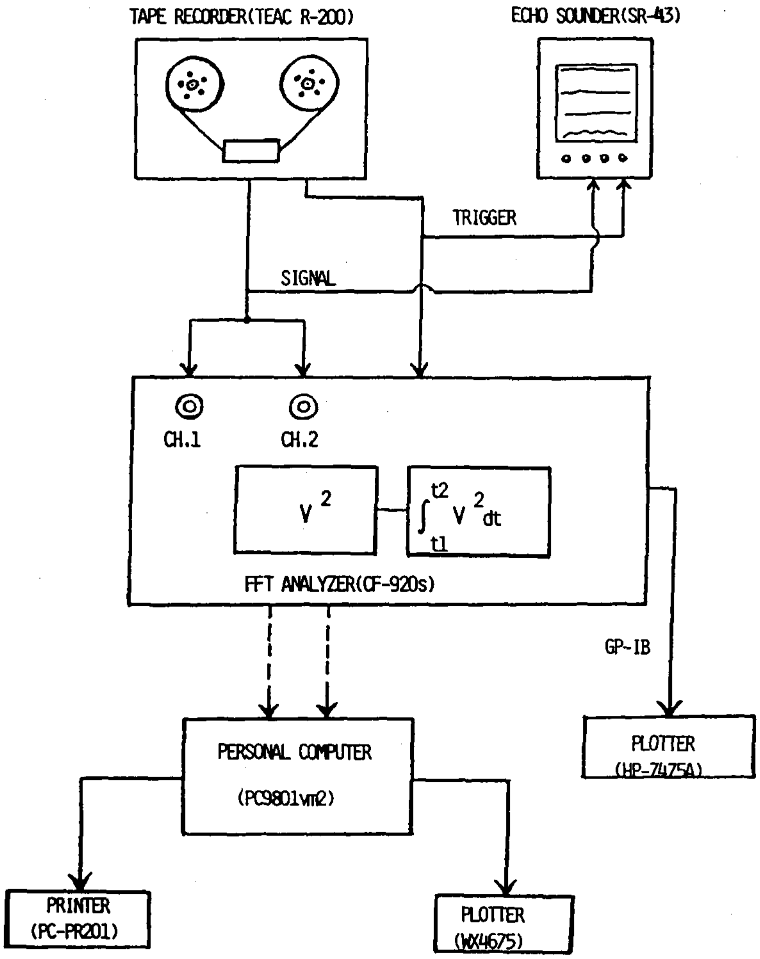


Fig. 4. Block diagram of data acquisition and processing system.

$$\langle SV \rangle = 10 \log \{(\langle E_{cs} \rangle - \langle E_c \rangle)/\langle E_r \rangle\} + \langle TS_r \rangle - 10 \log N + 10 \log \rho, \qquad (8)$$

where $\langle E_{cs} \rangle$ is the mean echo energy of squid and cage, $\langle E_c \rangle$ is the mean echo energy of the empty cage, $\langle E_r \rangle$ is the mean echo energy of the reference target, $\langle TS_r \rangle$ is the mean target strength of the reference target (-39.79 dB), N is the number of squid in the cage, and ρ is the density of squid in each cage series of experiments (squid/m^3). The results were printed out on a printer (NEC PC-PR-201) or on a plotter (WATANABE WX-475). Some hardcopy from FFT Analyzer was also printed with GP-IB by HP-7475A or EPSON HI-80 plotters. The block diagram of this data acquisition and processing system is shown in Fig. 4.

Finally, $\langle SV \rangle$ was regressed on ρ by least mean squares regression,

$$\langle SV \rangle = a + b \log \rho, \qquad (9)$$

and the results then represented together with their source data (as a scatter diagram) for each ensonifying frequency.

Results and Discussion

1. *Probability distribution of echo amplitude*

As noted above, the basic acoustic measurement was based on the measurement of the echo energy from encaged aggregations of similar squid relative to the

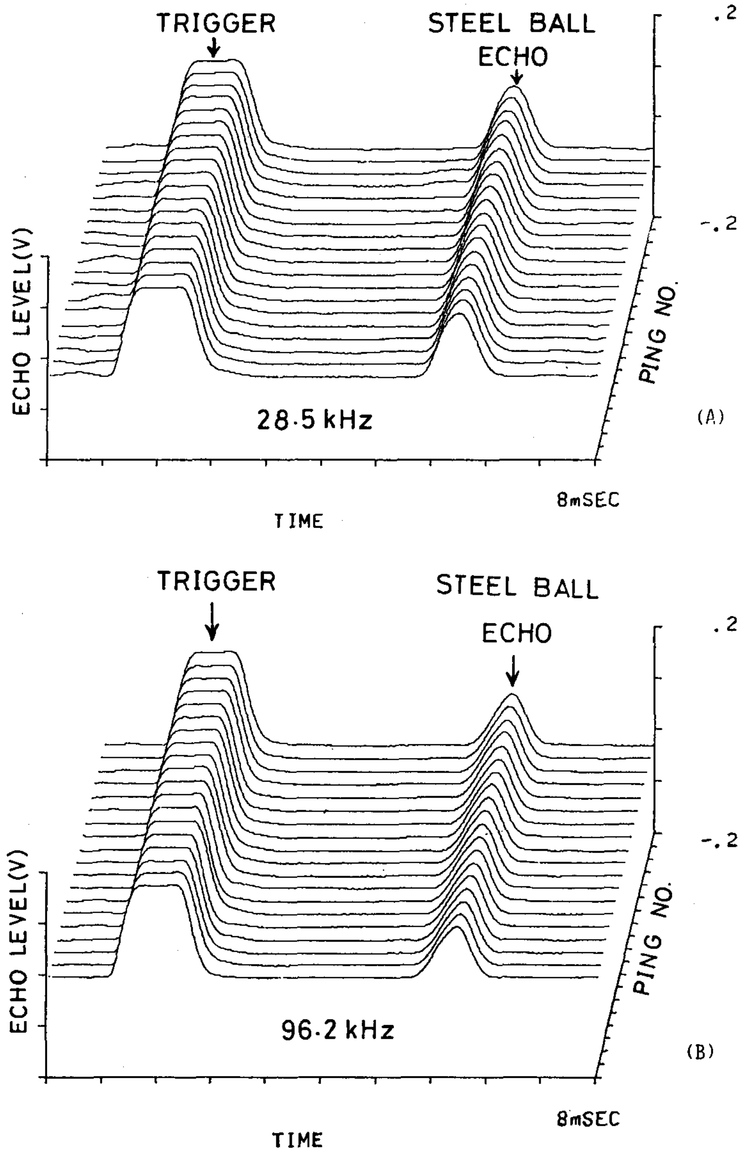


Fig. 5. Three-dimentional plots of the reference target echoes. (A) 28.5 kHz, (B) 96.2 kHz.

reference target. A standard steel ball of diameter of 41 mm was considered suitable as a reference target because of its stable echo signals during measurement. The stability of this reference target's echoes for both ensonifying frequencies are described in three-dimentional plots in Fig. 5.

In this measurement, the net cage in which the squid were contained was constructed to minimize its echo and this could be completely separated from that of the ring's echoes. As shown in Fig. 6, the cage echoes were small, relatively stable, and can be presumed to be negligible. However, for more accurate computation, a simple compensation in the energy domain has been applied.

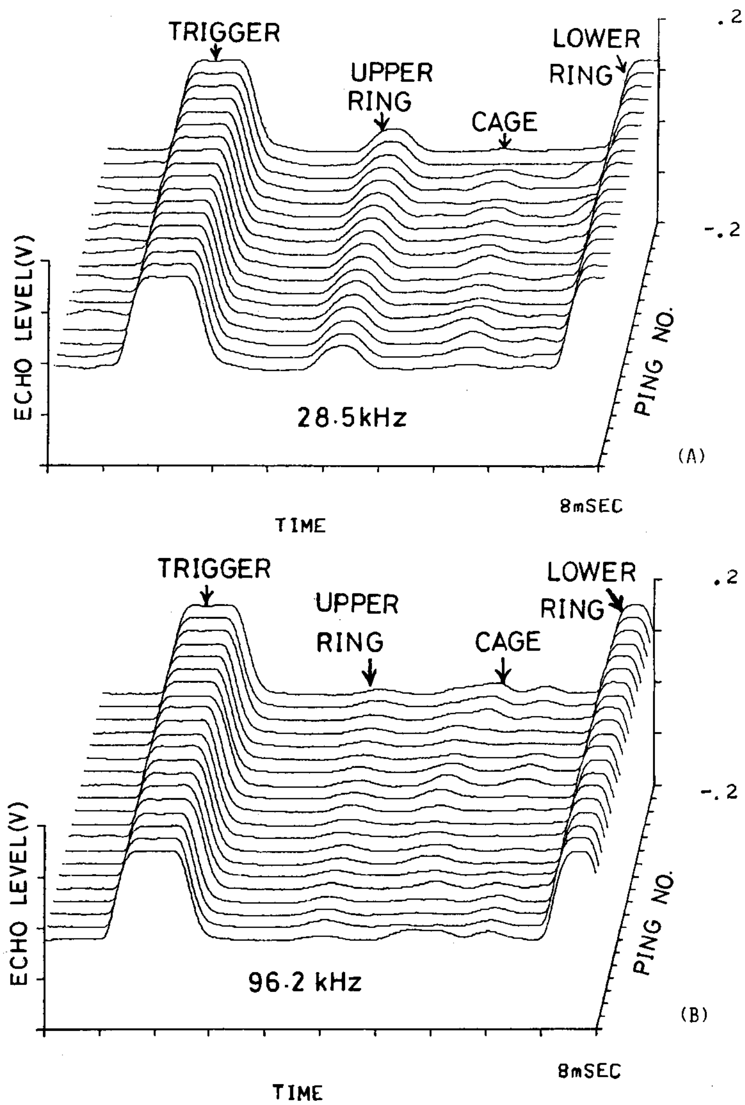


Fig. 6. Three-dimentional plots of the empty net cage echoes. (A) 28.5 kHz, (B) 96.2 kHz.

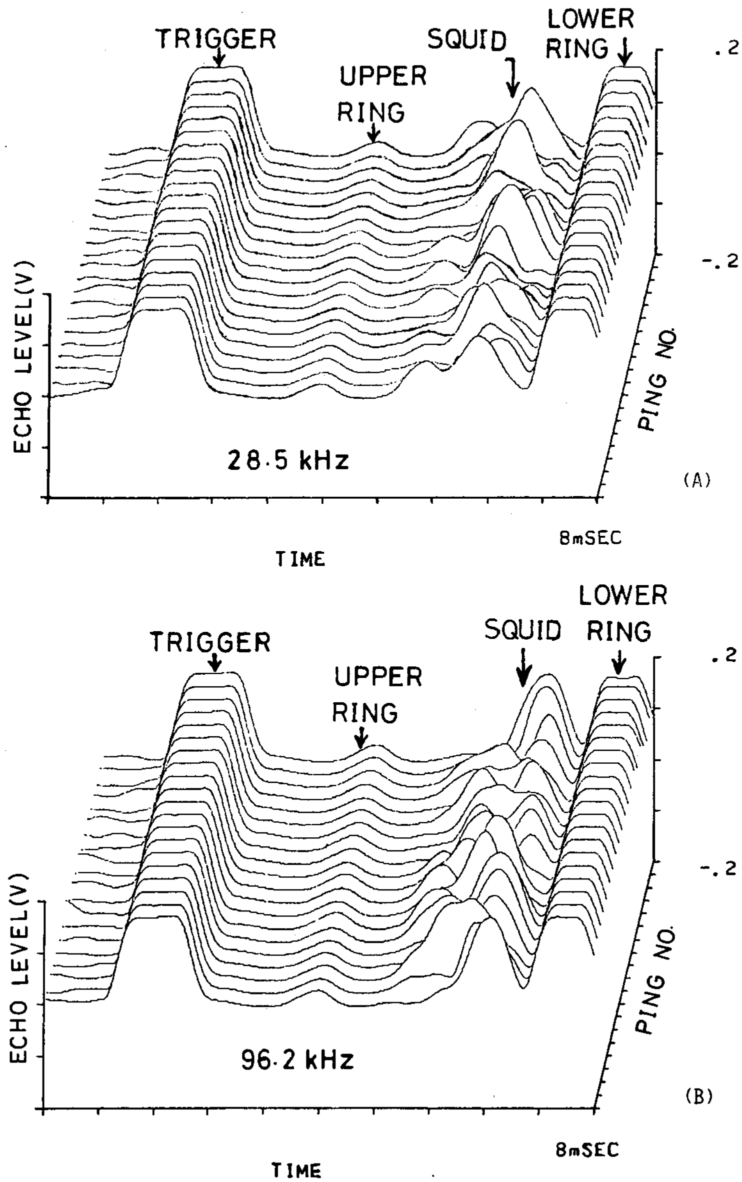


Fig. 7. Three-dimentional plots of the 32 encaged squids echoes. (A) 28.5 kHz, (B) 96.2 kHz.

The fluctuations in the individual pings of encaged aggregations of squid as shown in Fig. 7 for a density of 50 squid/m^3, may depend on the three major factors, namely length, position, and orientation as described in Equation (6) above. Because underwater photographic observations have not been conducted for the present experiments, the spatial distribution of squid in the net cage was assumed to be uniform, and the orientation distribution was assumed to be normal in the tilt angle. The dominant factor controlling the fluctuation of the echo amplitude is the way the squid move about or orient. Further evidence can also be gleaned from the way in which the echo sounder readings fluctuate as a function of time.

It was assumed, especially for densities from 50 to 125 squid/m^3, that "lively behaviour" (squid move, changing positions smoothly and regularly) probably most closely approximate the movement of free squid. "Wild behaviour" (squid struggle to get out of the net cage, horizontal and vertical displacements are large and wild) also occurred just after the squid were placed in the cage, and was not included in measurement; and for the highest density of 173 squid/m^3, "still behaviour" (squids without apparent movement) was considered to occur because some squid were injured or simply resting on the bottom of the cage. Therefore, only probability density function (PDF) of peak echo amplitude for density of 50 squid/m^3 was chosen and analyzed, and the results then compared with the results of preliminary measurements for 1.5 squid/m^3 density. As shown in Fig. 8, both for 28.5 kHz and 96.2 kHz, theoretical (Rayleigh) PDFs gave quite a good fit for the 1.5 squid/m^3 density; however for the 50 squid/m^3 density, the theoretical PDF was quite

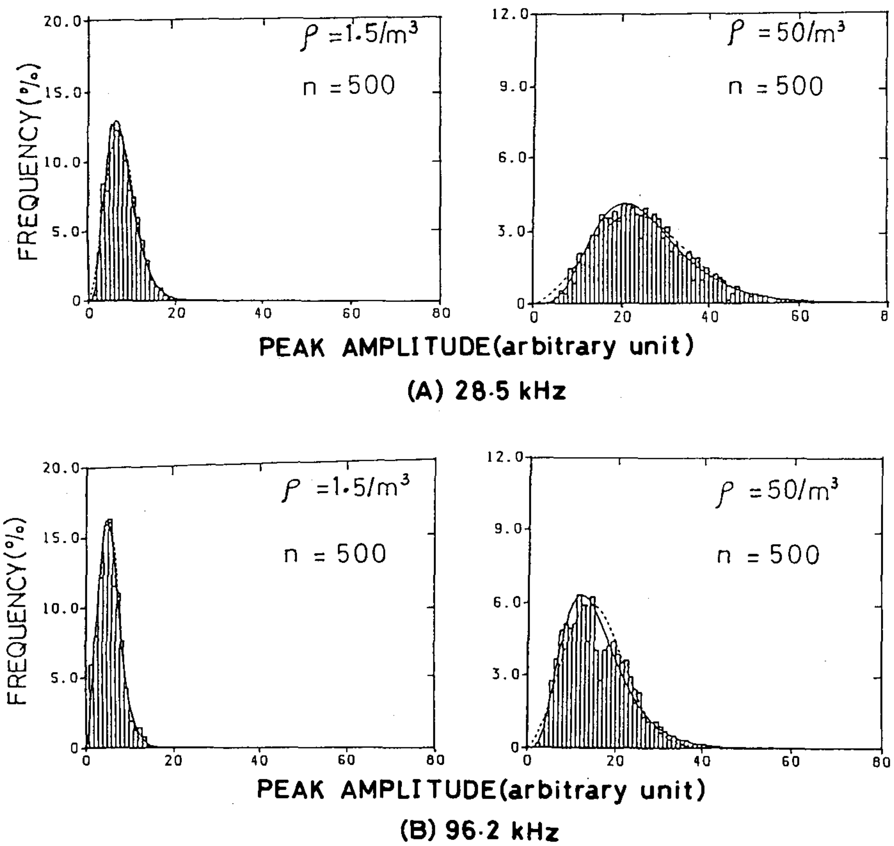
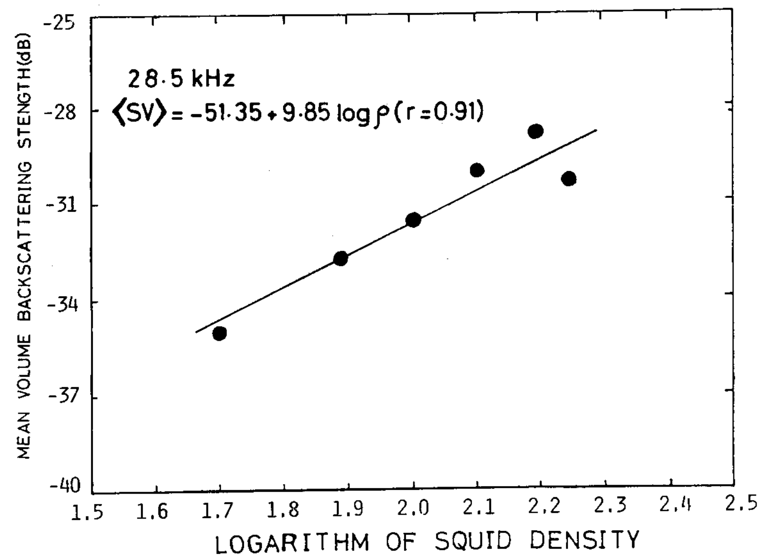


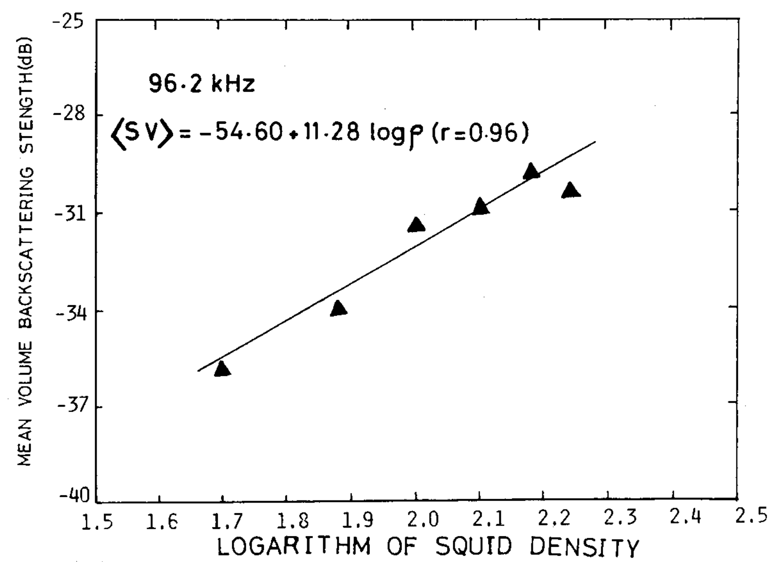
Fig. 8. Measured peak echo amplitudes PDFs of the squid echoes with theoretical (Rayleigh) PDF (------) and generalized Gamma PDF (——). (A) 28.5 kHz, (B) 96.2 kHz.

inaccurate, and a generalized Gamma PDFs[6,7] gave a better fit than the theoretical PDF.

Due to the fact that echo waveforms fluctuated from ping to ping during measurements as described above, or that variations in individual pings were much higher, the mean echo energy determined over 500-ping sequences was needed.



(A)



(B)

Fig. 9. The relationship between mean volume backscattering strength $\langle SV \rangle$ and squid density ρ at 28.5 kHz(A) and 96.2 kHz(B).

According to FOOTE[3], the merging of data in 500-ping sequences was considered justified. These mean echo energies were then applied in computation of mean volume backscattering strength for different squid densities and ensonifying frequencies.

2. The relationship between mean volume backscattering strength and squid density

The measured values of mean volume backscattering strength $\langle SV \rangle$ as computed by Equation (8) for each of the two ensonifying frequencies are plotted against squid density ρ in the form of a scatter diagram in Fig. 9. According to Equation (9), the least mean square regression of $\langle SV \rangle$ is shown together with its source data in the same figure. The regression may be expressed as

$$\langle SV \rangle = -51.35 + 9.85 \log \rho \quad (r = 0.91) \tag{10}$$

for 28.5 kHz, and

$$\langle SV \rangle = -54.60 + 11.28 \log \rho \quad (r = 0.96) \tag{11}$$

for 96.2 kHz.

These results confirmed the theoretical premise of linear dependence of the echo energy on the density of relativelly small-sized squid in an aggregation. It fulfilled the assumption that a sufficient number of observations are made under conditions of low-noise, a constancy of squid behaviour and negligibility of acoustic extinction. Thus, in the absence of acoustic extinction, the total echo energy is the sum of independent contributions from each squid of the aggregation, where the contributions depend on squid behaviour and ther factors as expressed in Equation (6).

Also, from the empirical $\langle SV \rangle$ to ρ relationships for surume ika of mean dorsal mantle length of 16.0 cm as described above, it is considered that those relationships are generally insensitive to ensonifying frequency. This is because the size-to-wavelength ratio or the proportional quantity $ka = 2\pi a/\lambda$, where a is equal to dorsal mantle length, k is the wavenumber, and λ is the wavelength of the signal at its frequency, is in excess of unity for 28.5 kHz, and much greater than unity for 96.2 kHz. Consequently, the phenomenon of scattering is essentially geometric. Thus, if other factors remaining unchanged, a change in magnitude of the ensonifying frequency above 28.5 kHz should not affect the relationship of $\langle SV \rangle$ and ρ.

However, for larger sizes of squid, and if the density is large enough so that acoustic extinction is significant, this simple theorem must be revised as also described by FOOTE[3] by his Theorem II. As is well known for a "bladder fish" target[8], with denser concentrations in the cage (*i.e.* when the distance between neighbouring fish is commensurable with acoustic wave length), the scattering fields of individual fish affect each other and a "multiple scattering phenomenon" take place (*i.e.* each fish, in scattering the acoustic wave, ensonifies nearby fish targets which also scatter part of the energy and so on). The resulting echo signals show signs of coherence, of interference and diffraction that are not considered in the linear model. An investigation of this interesting phenomenon for "bladderless fish", such as squid, will be conducted in the next study.

3. Mean dorsal aspect target strength

As shown in Equation (7) above, assuming that the squid in the cage are uniformly distributed in the volume ensonified by the echo sounder, and if multiple scattering is ignored, the mean target strength can be calculated from $\langle SV \rangle$ because the number or density of encaged squid is known. The validity of the estimation of the mean target strength by this method was also supported by the result described above because the intercepts of the regression lines in Equations (10) and (11) are very close to the theoretical value of 10. Thus, for the relatively small sizes of squid measured (mean dorsal mantle length of 16.0 cm), the mean dorsal aspect target strength was -51.35 dB for 28.5 kHz and -54.60 dB for 96.2 kHz.

Furthermore, if the values of these mean target strengths are compared with those of from dead and tethered squid in anechoic water tank (but for different ensonifying frequencies) as reported in the previous study[4,9], these values seem too small, but very similar to the values obtained from *in situ* measurements of market squid (*Loligo opalescens*)[10]. These mean target strength values are also much lower than those for bladder fish of the same size[11]. This was expected due to the lack of a gas-filled swimbladder in squid. So, measurements of target strength of squid must be performed in sea water because of their sensitivity to the density and sound speed differences between body fluid and surrounding medium. Finally, the present findings are very important from stock assessment point of view, and in the future additional study is needed to gather more detailed knowledge of this squid target strength properties.

Conclusions

Experiments to describe the squid density dependence of acoustic backscattering strength of an aggregation of encaged, free swimming squid in relation to the verification of the integration method, and to estimate the mean target strength of relatively small sizes of surume ika, were performed.

Based on these measurmements, it can be summarized:

(1) The echo integration method of determining squid density is valid and the phenomenon of acoustic scattering by squid under the described conditions is strictly linear.

(2) The relationships between mean volume backscattering strength $\langle SV \rangle$ and squid density ρ(squid/m^3) were:

$$\langle SV \rangle = -51.35 + 9.85 \log \rho \quad (r = 0.91), \text{ for } 28.5 \text{ kHz},$$

and

$$\langle SV \rangle = -54.60 + 11.28 \log \rho \quad (r = 0.96), \text{ for } 96.2 \text{ kHz}.$$

(3) The measured mean target strength of surume ika of 16.0 mean dorsal mantle length was -51.35 dB for 28.5 kHz, and -54.60 dB for 96.2 kHz.

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