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Studies on Acoustic Target Strength of Squid
IV. Measurement of the mean target strength of relatively large-sized live squid

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Abstract

As an advancement of the previous study, experiments were performed to describe the dependence on squid density of acoustic backscattering strength of an aggregation of encaged, free swimming live squid in relation to the verification of the echo integration method, and to estimate the mean dorsal aspect target strength of relatively large-sized squid. In these experiments, various numbers of surume ika (*Todarodes pacificus*), with a mean dorsal mantle length of 23.67 cm and mean body weight of 340.2 g, were introduced into a net cage of approximately 0.64 m^3 in volume.

The results can be summarized as follows:

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

$\langle SV \rangle = -45.66 + 8.96 \log \rho (r=0.95)$ for 28.5 kHz,
$\langle SV \rangle = -46.53 + 8.98 \log \rho (r=0.94)$ for 50 kHz,
$\langle SV \rangle = -48.04 + 10.17 \log \rho (r=0.95)$ for 96.2 kHz,
and $\langle SV \rangle = -47.62 + 9.91 \log \rho (r=0.93)$ for 200 kHz.

(2) The estimated mean dorsal aspect target strengths were −45.66 dB for 28.5 kHz, −46.53 dB for 50 kHz, −48.04 dB for 96.2 kHz, and −47.62 dB for 200 kHz.

Introduction

In a recent paper[1)] experiments to describe the dependence on squid density of acoustic backscattering strength of an aggeration of encaged, free swimming squid in relation to the verification of the echo integration method, and to measure the mean dorsal aspect target strength of relatively small sizes squid, were reported. Surume ika (*Todarodes pacificus*) of a mean dorsal mantle length of 16.0 cm and mean body weight of 95.1 g were the subject of the measurements because of the local abundance at the time of the experiments, but until now there has been no data on live squid's target strength. The measurements were performed from a specially designed platform at Usujiri fishing port's pier, Minami Kayabe, Hokkaido. The most important results were the verification of the validity of the echo integration method of determining squid density and the verification of the strict linearity of the phenomenon of acoustic scattering by squid under the described conditions.

Similar to and as an advancement of the previous paper, this paper describes experimental results of the mean target strength of the same species, but of relatively

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large-sized live squid. The measurements were performed from the same platform as the previous experiments, however, at "Hokusei Maru" training vessel of Hokkaido University.

Materials and Methods

1. *Review of Theory*

A physical model for acoustic scattering by fish aggregation (as formulated by FOOTE[2~4] and reviewed in the previous paper[1]) in accordance with the basic linearity of fisheries acoustics is applied in the present study to the problem of the scattering of sound by an encaged aggregation of dorsally ensonified large-sized squid.

The possibility of multiple scattering by dense or extended fish schools has worried some researchers for years. This concern is shown to be unfounded by reference to the larger literature. According to the general and specific evaluations, actual densities of natural fish aggregations never support the occurrence of multiple scattering[5,6]. For squid, CAILLIET and VAUGHAN[7] observed that density estimates of market squid using an underwater video system at various locations next to Santa Catalina lsland, California were from 1.6 to 106.7 squid/m^3. So, these densities are far from the limits within which the multiple scattering or first order scattering models would be valid, i.e. 3.23×10^4/m^3 for gadoids of 96 cm length as considered by FOOTE[5].

The validity of the linear model in fisheries acoustics is now adopted for the case of squid, and for convenience this phenomenon will be reviewed again in this paper as described below.

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 and in the absence of extinction, then the equivalent received pressure field p_{rec} is just

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

And if the density, vertical extent, and mean extinction cross section σ_e of the fish are large enough so that extinction is significant, then Equation (1) may be generalized by analogy with optics or quantum scattering theory at least to the first order in the extinction parameter and in the mean of a large number of observations,

$$p_{rec}=\exp\left(-2\rho\sigma_e\Delta z\right)\cdot\sum_{i=1}^{n} p_{rec,i} \tag{2}$$

wher $p_{rec,i}$ is the component due to the i-th fish of n, where there is no extinction, ρ is the fish density, and Δz is the thickness of the layer of fish distribution. 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),

$$p_{rec,i}=(Gb^2\sigma)_i^{1/2}s_i \tag{3}$$

where s_i is the echo waveform, which is generally different from that of the ensonifying signal. The several factors in Equation (3) 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

$$I=(\rho_w c_w)^{-1} p_{rec}^2 \tag{4}$$

where $\rho_w c_w$ is acoustic impedance (ρ_w and c_w are the density and sound speed of the medium, respectively). The product $\rho_w c_w$ is a 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

$$E=\int_0^\infty I(t)dt=(\rho_w c_w)^{-1}\int_0^\infty p_{rec}^2(t)dt \tag{5}$$

where the integral, in the practical case, is taken over the duration of the received echo signal. It is necessary to remember that the echo energy E is the same whether it's expressed in the frequency domain or the time domain, and it does not depend upon the system phase resonance. However, it does depend on the pulse shape, and it 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 backscattering 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 a fish aggregation, in the absence of noise, can be written,

$$\langle E\rangle=c_1\rho\langle\sigma\rangle, \tag{6}$$

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

$$\langle\sigma\rangle=\int Gb^2\sigma dF \Big/ \int Gb^2 dF, \tag{7}$$

where dF is the probability element associated with squid position, orientation distribution, length, and other possible variable characteristic of fish in an aggregation, such as species, condition when observed acoustically, and behaviour insofar as social interactions which may influence the fish as acoustic scatterers. These averaging models of backscattering cross section have been examined in the previous study[8] and are beyond the scope of this paper.

In logarithm form, Equation (6) can be simplified as

$$\langle SV\rangle=10\log\rho+\langle TS\rangle. \tag{8}$$

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 large-sized live squid.

2. *Materials*

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

The number of squids used for the measurements was 123 ; dorsal mantle length and body weight histograms are presented in Fig. 1. The mean dorsal mantle length and body weight were 23.67 cm and 340.2 g, respectively.

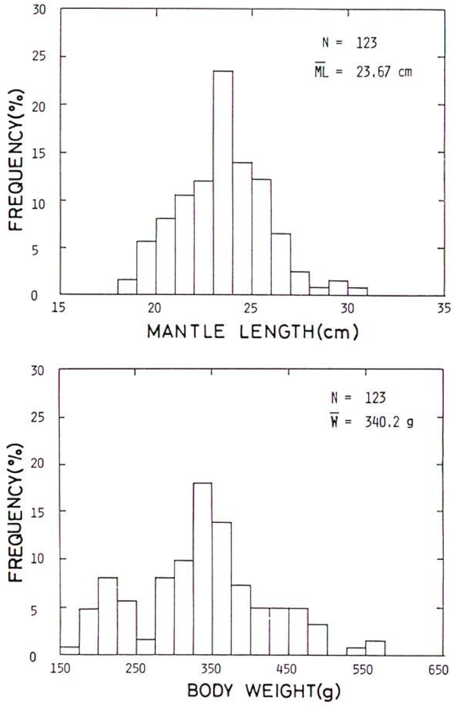

Fig. 1. Frequency distributions of dorsal mantle length and body weight compositions of surume ika used in measurements.

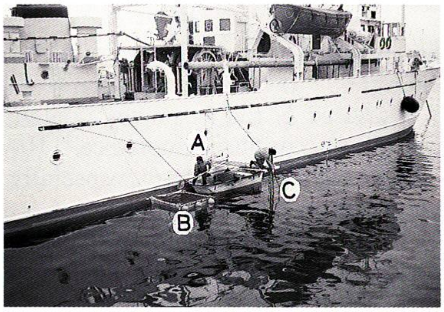

Fig. 2. Measurement configuration at Hokusei Maru.
(A) platform, (B) squid preserve, and (C) transducers.

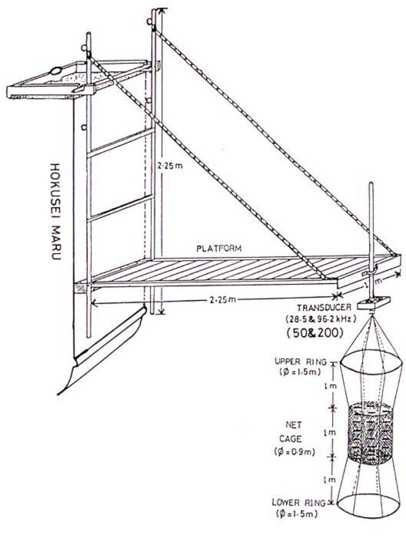

Fig. 3. Experimental set-up.

3. *Experimental set-up*

The measurements were performed from a specially designed platform at "Hokusei Maru" training vessel of Hokkaido University which was anchored in Hakodate port (See Fig. 2). The average water depth was 8.0 m, and 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 had no effect on the experiment because of the large size of the vessel (893 GT).

The experimental setup is shown in Fig. 3. 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 (a standard steel ball with a diameter of 41 mm) at a depth of 5.5 m. The net cage was designed similarly to those of ROTTINGEN's study[9]. 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 a 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 a 1 m distance from the net cage; thus the echoes from these rings were not included in the integration.

All acoustic (squid) measurements were performed relative to the reference target. Measurements of this reference target and the empty net cage were conducted before the squid measurements. Before any acoustic measurements were made, the net cage was hoisted to the water's surface, and the desired number of squid were transfered through an opening on the pop of the net cage. Then the net cage was lowered to the desired depth. The numbers of squid introduced into the net cage

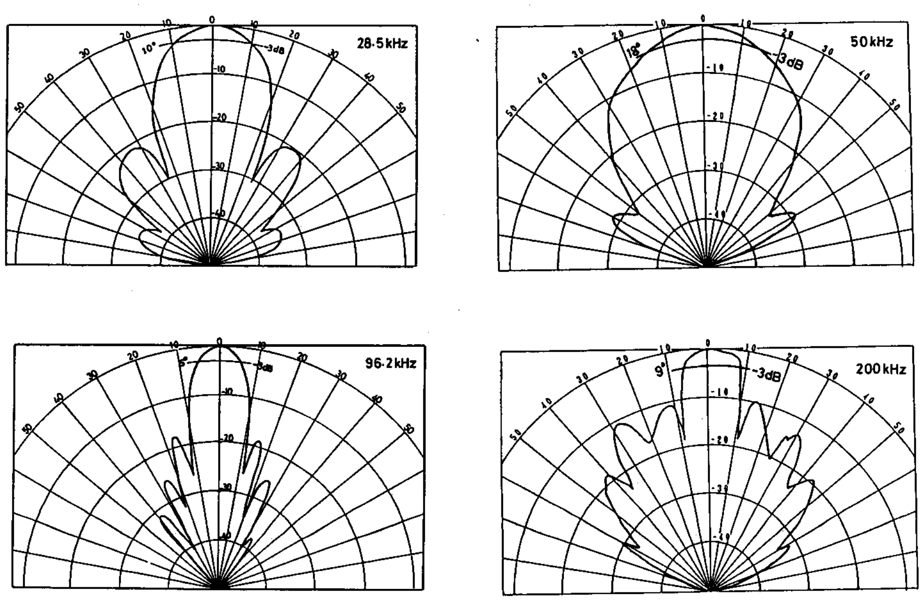

Fig. 4. Directivity pattern of transducers.

were 1, 2, 3, 4, 5, 8, 11, 15, 21, 30, 41, 58, and 82 squid, or densities of 1.56, 3.12, 4.69, 6.25, 7.81, 12.50, 17.19, 23.44, 32.81, 46.87, 64.06, 90.62, and 128.12 squid/m^3.

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; and a JRC JFV-216 echo sounder, which had two frequencies of 50 kHz and 200 kHz, and two pulse durations of 0.5 ms and 0.2 ms, respectively. Each of the four transducers had a beamwidth of 10, 18, 5, and 9 deg for 28.5 50, 96.8, and 200 kHz, respectively. The directivity pattern of these transducers is shown in Fig. 4. Some of the associated electronic equipment that is not described in Fig. 3, included a seven channel Data Recorder (TEAC XR-310) (only four channels were used in this experiment) and a three channel Oscilloscope (KIKUSUI Com-7101A) for continual monitoring of signals during recording on a 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 video cassette of the data recorder. Each complete measurement involved the recording of approximately 500 successive pings of a given density and ensonifying frequency. The recorded data was analyzed later in the laboratory.

4. Data processing

The two channels of an 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 video cassette was played back and the echo signals were 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 using the 51.2 kHz sampling frequency, or along a display time scale of 8 ms with a 0.0078 ms sampling interval. In the second operation, the digitized echo signal was squared and time integrated for each of the sequence of 500 pings. The mean echo energy for each squid density and it's ensonifying frequency was obtained by averaging all of the 500 echo energies by personal computer (NEC PC-9801vm2).

In the analysis of the encaged squid aggregation series, the measured average echo energy due to the empty net cage and reverberation was 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

$$\langle SV \rangle = 10 \log \{(\langle E_{cs} \rangle - \langle E_c \rangle)/\langle E_r \rangle\} + \langle TS_r \rangle - 10 \log N + 10 \log \rho, \qquad (9)$$

where $\langle E_{cs} \rangle$ is the mean echo energy of the 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 the cage in each 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 hardcopies from the FFT Analyzer were 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. 5.

Finally, $\langle SV \rangle$ (dB) was regressed on ρ (squid/m^3) by least mean squares regression,

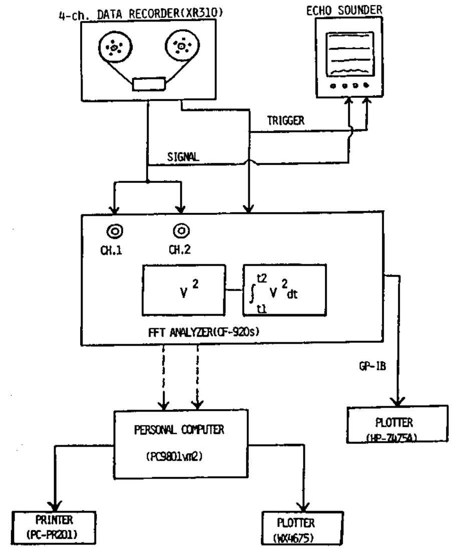

Fig. 5. Block diagram of data acquisition and processing system.

$$\langle SV \rangle = a + b \log \rho, \tag{10}$$

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

Results and Discussion

1. Fluctuation 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 reference target. A standard steel ball with a diameter of 41 mm was considered suitable as a reference target because it provide stable echo signals during measurement. The stability of this reference target's echoes for four ensonifying frequencies is described in three-dimensional plots in Fig. 6. In this figure and also in the Fig. 7 and Fig. 8, the bottom and ring's echoes were sometime saturated to made the target echoes clear and large.

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. 7, the cage echoes were small and relatively stable, and for more accurate mean volume backscattering strength computation a simple compensation in the energy domain has been applied.

The fluctuations in the individual pings of encaged aggregations of squid, for example as shown in Fig. 8 for a density of 32.81 squid/m^3, may depend on three major factors, namely length, position, and orientation as described in Equation (7) above. Because underwater photographic observations were not conducted for these present experiments, the spatial distribution of squid in the net cage was

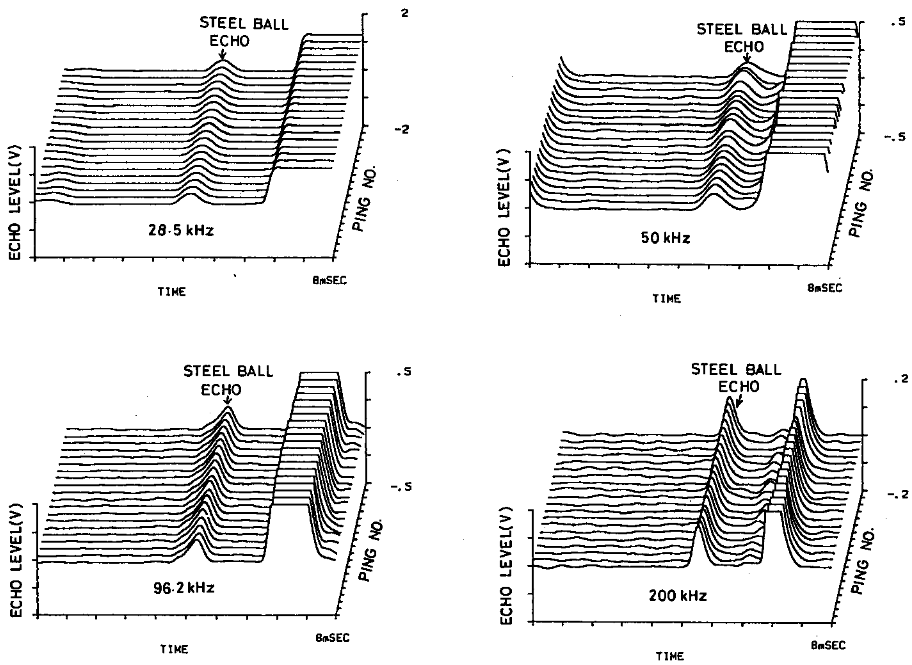

Fig. 6. Three-dimensional plots of the reference target echoes.

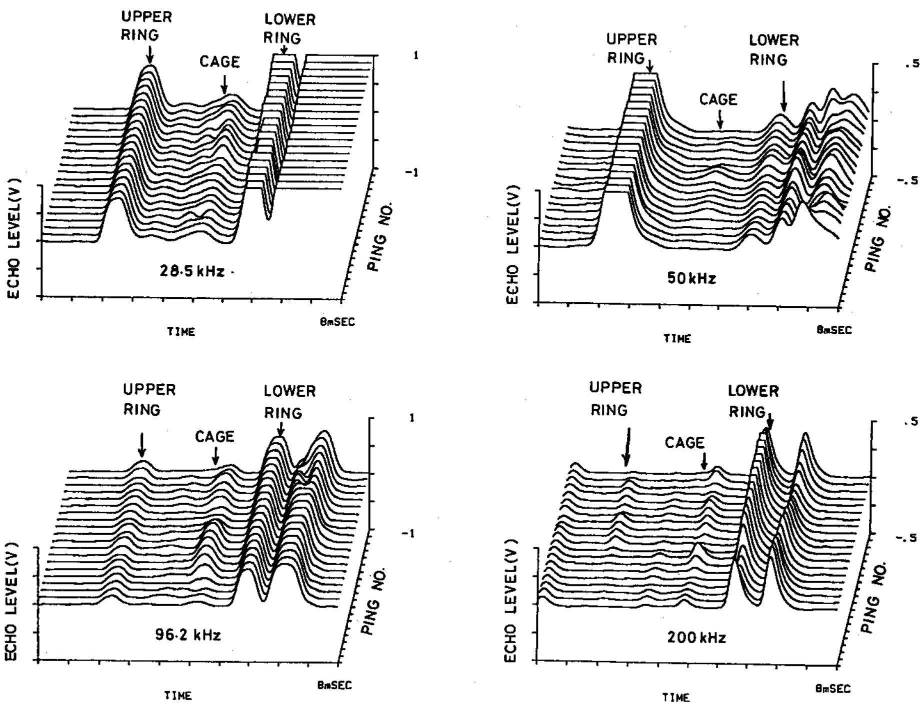

Fig. 7. Three-dimensional plots of the empty net cage echoes.

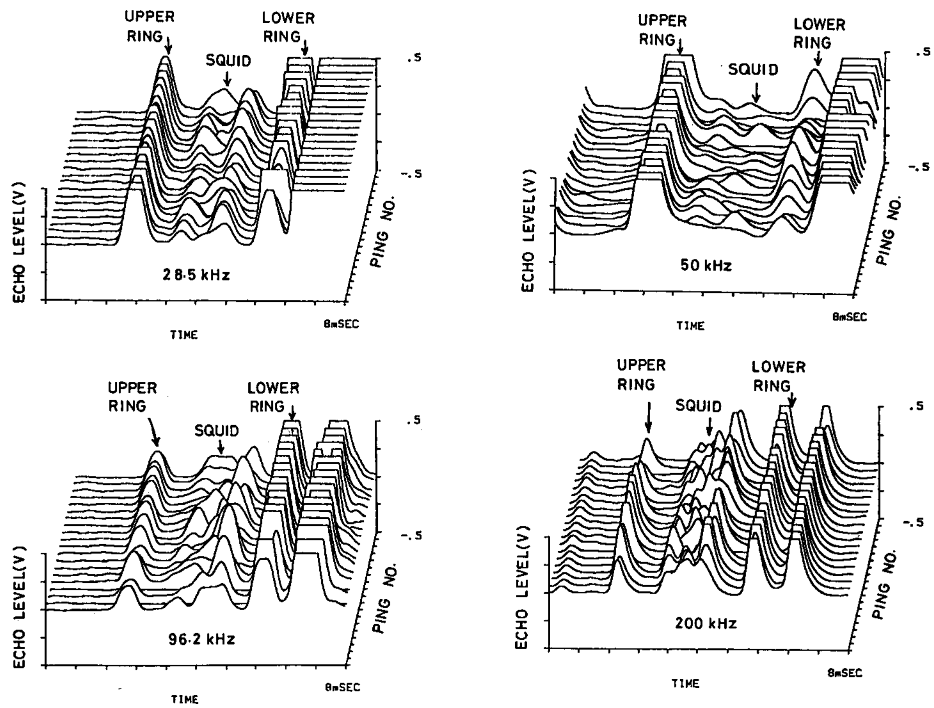

Fig. 8. Three-dimensional plots of the encaged squids echoes.

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 1.56 to 90.62 squid/m^3, that "lively behaviour" (squid movement involving changing of positions smoothly and regularly) probably most closely approximates the movement of free squid. "Wild behaviour" (squid struggling to get out of the net cage causing large and wild horizontal and vertical displacements) also occurred just after the squid were placed in the cage, and was not included in measurement; and for the highest density of 128.12 squid/m^3, "still behaviour" (squid without apparent movement) was considered to occur because some squid were injured or simply resting on the bottom of the cage.

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. According to FOOTE[4], the merging of data in 500-ping sequences was considered justified. There mean echo energies were then applied to the computation of a 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 $\langle SV \rangle$ (dB) as computed by Equation (9) for each of the four ensonifying frequencies are plotted against squid density ρ (squid/m^3) in the form of a scatter diagram in Fig. 9 for 28.5 and 96.2 kHz, and in Fig. 10 for 50 and 200 kHz. According to Equation (10), 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

$$\langle SV \rangle = -45.66 + 8.96 \log \rho (r=0.95) \text{ for } 28.5 \text{ kHz}, \quad (11)$$
$$\langle SV \rangle = -46.53 + 8.98 \log \rho (r=0.94) \text{ for } 50 \text{ kHz}, \quad (12)$$
$$\langle SV \rangle = -48.04 + 10.17 \log \rho (r=0.95) \text{ for } 96.2 \text{ kHz}, \quad (13)$$

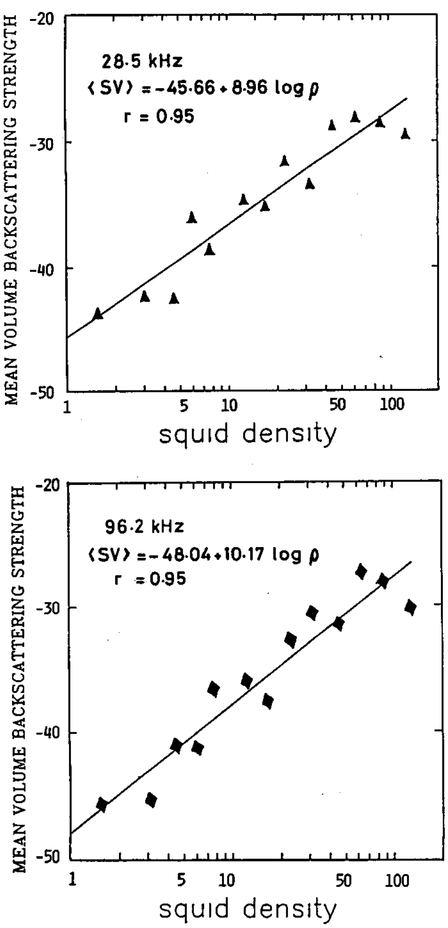

Fig. 9. The relationship between mean volume backscattering strength $\langle SV \rangle$ (dB) and squid density ρ(sequid/m^3) at 28.5 kHz and 96.2 kHz.

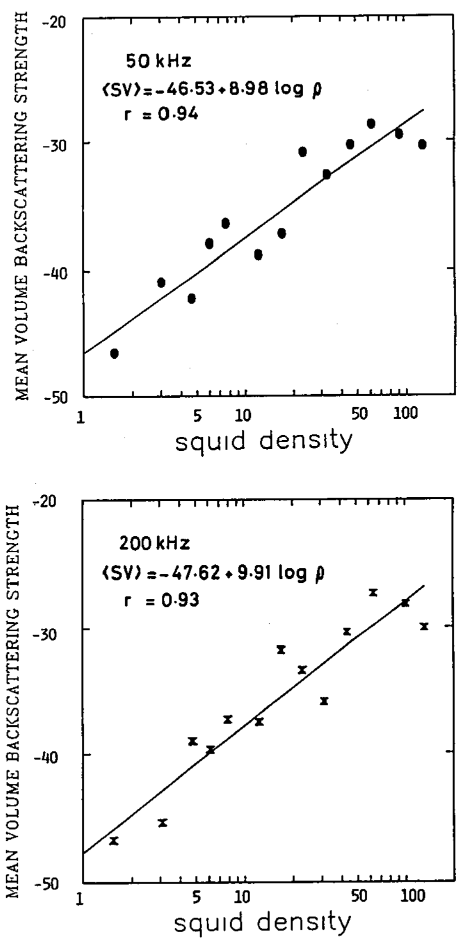

Fig. 10. The relationship between mean volume backscattering strength $\langle SV \rangle$ (dB) and squid density ρ(sequid/m^3) at 50 kHz and 200 kHz.

and $$\langle SV \rangle = -47.62 + 9.91 \log \rho (r = 0.93) \text{ for } 200\,\text{kHz}. \tag{14}$$

These results also confirm the theoretical premise of linear dependence of the echo energy on the density of relatively large-sized squid in an aggregation. It fulfills the assumption that a sufficient number of observations are made under conditions of low-noise, constant squid behaviour and negligible 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 other factors as expressed in Equation (7).

Also, from the empirical $\langle SV \rangle$ (dB) to ρ(squid/m^3) relationships for surume ika of mean dorsal mantle length of 23.67 cm as described above, it is considered that those relationships are generally insensitive to both ensonifying frequency and pulse duration. 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 other ensonifying frequencies. Consequently, the phenomenon of scattering is essentially geometric. Thus, if other factors remain unchanged, a change in magnitude of the ensonifying frequency above 28.5 kHz should not affect there relationship of $\langle SV \rangle$ and ρ.

The relative insentitivity of the $\langle SV \rangle$-ρ relationship to changes in pulse duration can also be understood rather simply. The pulse-to-pulse variations in the echo energy were large, suggesting both the importance of coherence for a particular echo energy and the fact that the squid did not remain stationary, but moved about. That this internal movement provides a mechanism for the randomness of echo energy is clear, for while the ensonifying signal was narrowband, the squid densities were always such that the mean nearest-neighbour squid distance was much greater than the wavelength. Thus the phases or relative times of the constituent echoes from individual squid, which compose the whole echo, are entirely random. The effect of this is to cause the coherent contribution to echo energy to vanish in the mean of large numbers of independent observations of echo energy at particular squid density, so that mean echo energy is equal to the irredicible incoherent contribution alone. This non-vanishing component of mean echo energy is linearly proportional to the pulse duration as is the energy contained in the ensonifying signal.

The implication of the insensitivity of the $\langle SV \rangle$-ρ relationship to ensonifying frequency and the pulse duration for these experiments is that the phenomenon of echo formation by an encaged aggregation of squid at ultrasonic frequencies is primarily geometric and incoherent. The principal evidence for this conclusion is that a variation in ensonifying frequencies and pulse durations, thence phase, with corresponding changes in the squid size-to-wavelength ratio and mean squid separation-to-pulse length ratio, have only an indiscernible effect on the squid density-dependence of the mean echo energy. If the mean echo energy were very dependent on the coherent or physical effect of interference among the constituent echoes, then there almost certainly would have been considerable variations in the $\langle SV \rangle$-ρ relationship as ensonifying frequency and pulse duration were veried; yet, the variations which were present are slight and apparently even too inconsistent to justify speculation about the origin. The fact that the $\langle SV \rangle$-ρ relationship is stable with respect to large changes in both pulse duration and ensonifying frequency for the same kind of squid of relatively uniform size distributions, strengthens the conviction that a purely geometric theory of scattering should be entirely adequate to explain the quantitative features of the $\langle SV \rangle$-ρ relationship.

3. *Mean dorsal aspect target strength*

As shown in Equation (8) 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 (11), (12), (13) and (14) are very close to the theoretical value of 10.

Thus, for the relatively large-sized of squid measured (mean dorsal mantle length of 23.67 cm), the mean dorsal aspect target strength was −45.66 dB for 28.5 kHz, −46.53 dB for 50 kHz, −48.04 for 96.2 kHz and −47.62 dB for 200 kHz.

Furthermore, if the values of these mean target strengths are compared with those of dead and tethered squid in an anechoic water tank (but for different ensonifying frequencies) as reported in the previous study[8,10], these values seem too small, but very similar to the values obtained from *in situ* measurements of market squid (*Loligo opalescens*)[11]. These mean target strength values are also much lower than those for bladder fish of the same size[12,13]. This was expected due to the lack of a gas-filled swimbladder in squid. So, measurements of target strength of "bladderless fish", such as squid, must be performed in sea water because of their sensitivity to the density and sound speed differences between body fluid and the surrounding medium[14]. Finally, the present findings are very important from a stock assessment point of view, and in the future additional theoretical study is needed to gather more detailed knowledge about these squid target strength properties in accordance with the application of the echo integration method.

Conclusions

As an advancement of the previous study, experiments were performed to describe the dependence on squid density 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 large-sized of surume ika (*Todarodes pacificus*).

Based on these measurements, these experiments can be summarized:

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

$\langle SV \rangle = -45.66 + 8.96 \log \rho$ ($r = 0.95$), for 28.5 kHz,

$\langle SV \rangle = -46.53 + 8.98 \log \rho$ ($r = 0.94$), for 50 kHz,

$\langle SV \rangle = -48.04 + 10.17 \log \rho$ ($r = 0.95$), for 96.2 kHz,

and $\langle SV \rangle = -47.62 + 9.91 \log \rho$ ($r = 0.93$), for 200 kHz.

(2) The measured mean target strength of surume ika of 23.67 cm mean dorsal mantle length and 340.2 g mean body weight was −45.66 dB for 28.5kHz, −46.53dB for 50 kHz, −48.04 dB for 96.2 kHz and −47.62 dB for 200 kHz.

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