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FREQUENCY-SELECTIVE ATTENUATION OF SOUND PROPAGATION AND REVERBERATION IN THE YELLOW SEA

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In the summer of 1991, sound propagation and reverberation experiments were carried out in the Yellow Sea. Explosive sound sources and omnidirectional hydrophones were used. The sound speed profile consisted of a warmer surface isovelocity layer, a strong thermocline and a cooler isovelocity bottom layer. When both the source and the receiver were located above the thermocline, the transmission loss along a certain course and the non-directional average reverberation intensity showed similar frequency-selective attenuation at around 1300 Hz. On the basis of experimental results and some circumstantial evidence, the authors believe that the observed frequency-selective attenuation is due to swimbladder-bearing fish (probably, anchovies) living only above the thermocline.

1. INTRODUCTION

Anomalous attenuation of sound propagation was observed sometimes in the shallow waters of the Bristol channel, and it was attributed to fish having swimbladders [1]. When both the sound source and the receiver were located *below* a strong thermocline, abnormally large attenuation of sound propagation over a limited frequency range was also observed in summer in the Yellow Sea, and it was interpreted by scattering loss due to internal wave solitions [2]. It has been noted that attenuation due to fish could be the reason for the Yellow Sea anomaly [3].

In this paper, some experimental results obtained in the Yellow Sea using explosive sound sources are presented. When the source and the receiver were located *above* a strong thermocline, the frequency responses of the transmission loss along a certain course and the non-directional average reverberation intensity showed similar frequency-selective attenuation at around 1300 Hz. However, no

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anomalous attenuation was observed when the source and the receiver were below the thermocline. It is surmised that this anomalous behavior is due to fish living above the thermocline.

2. EXPERIMENTAL RESULTS

In August 1991, sound propagation and reverberation experiments were conducted in the Yellow Sea using explosive sound sources. During the transmission loss measurements, the source ship moved along the 135 and 060 courses, starting from the anchored receiving ship (Figure 1). Two kinds of source with the same weight of explosive charge (38 g TNT) were detonated at 7 and 25 m, respectively, while the source ship moved. Sound signals were received by two hydrophones suspended at depths of 7 and 25 m and then recorded by a 4-channel magnetic tape recorder at the receiving ship. During the reverberation measurements, dropping of explosive sources, receiving and recording of sound signals were all done at the receiving ship. The depths of detonation and the receiving hydrophones were the same as in the sound propagation experiment. Both hydrophones were omnidirectional. The water depth at the experimental sea area was about 40 m. Figure 2 shows a vertical sound speed profile, and it indicates that there is a strong thermocline.

The beginning and end times of the transmission loss measurements for the 135 course were 20:00 and 22:40 on 11 August; the beginning and end times of the transmission loss measurements for the 060 course were 02:00 and 05:00 on 12 August. The beginning and end times of the reverberation measurements were 20:00 and 20:40 on 12 August. The time of sunset was 18:55, and the time of sunrise was 05:16. These times are the local times. Therefore, these measurements were made after sunset but before sunrise.

The broadband propagation and reverberation signals recorded at sea were sampled, A/D transferred and processed by a computer in laboratory. The transmission loss (TL) at different ranges and the level of average reverberation intensity as a function of time were obtained for different centre frequencies within the frequency range 0·3–10 kHz. Figures 3–6 give the relative level to show the frequency-selective attenuation in the frequency range 1000–2000 Hz.

Figure 3 shows the frequency response of the transmission loss for source and receiver depths of 7 m along the 060 course. An obvious frequency-selective attenuation with a centre frequency of about 1300 Hz can be seen. In order to determine accurately the centre frequency of the frequency-selective attenuation, both the separation between two successive centre frequencies and the bandwidth were taken to be 50 Hz during digital filtering of the broadband signals.

Figure 4 shows the depth dependence of the transmission loss along the 060 course at a range of 5·7 km. No anomalous attenuation was observed when both the source and the receiver were at 25 m (below the thermocline). When the source and receiver were separately located above and below the thermocline (7 and 25 m), the frequency-selective attenuation also appeared, but it was less than that observed when both the source and the receiver were above the thermocline.

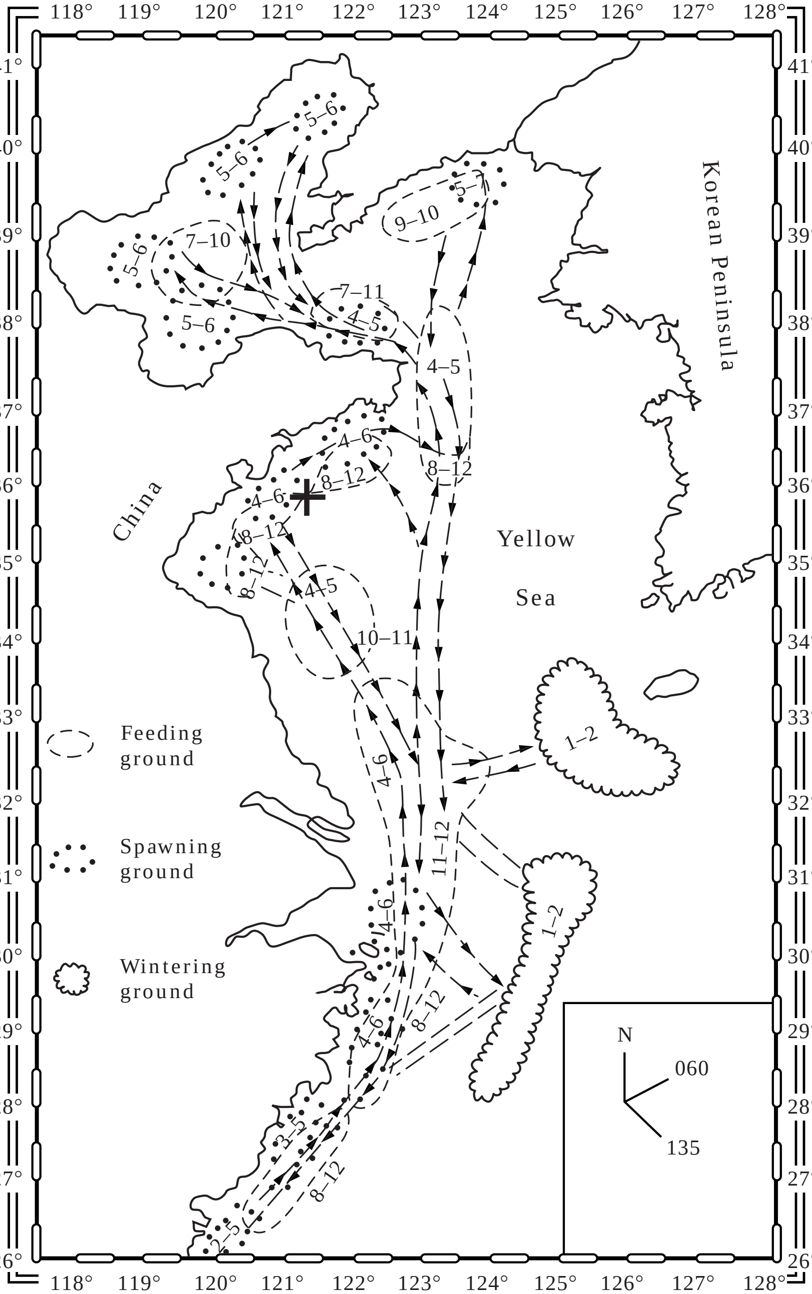

Figure 1. Experimental sea area and the moving directions of the source ship. The cross indicates the position of the anchored receiving ship. Two moving directions of the source ship are plotted at the bottom right corner. The migration route and feeding ground of the bluespotted mackerel are also shown in this figure (cited from reference [4]). The numbers, 1–2, 4–6, 8–12, etc. indicate January–February, April–June, August–December, etc., respectively.

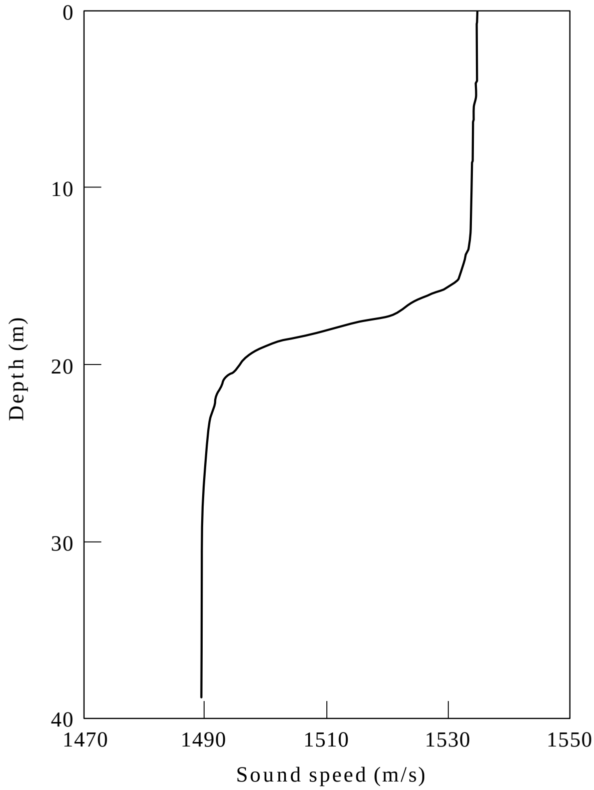

Figure 2. Sound velocity profile.

Figure 5 shows that the frequency-selective attenuation of the transmission loss was dependent on direction. The transmission loss along the 135 course showed no anomalous attenuation. The data in Figures 3–5 resulted from averaging three explosive signals.

An interesting and important result is that, as shown in Figure 6, when both the source and the receiver were at 7 m, the average reverberation intensity also showed an obvious frequency-selective attenuation with a centre frequency of about 1300 Hz. The data in Figure 6 resulted from averaging five explosive signals. However, when both the source and the receiver were located at 25 m, no anomalous attenuation of the average reverberation intensity was observed.

3. DISCUSSION

3.1. CAUSE OF THE FREQUENCY-SELECTIVE ATTENUATION

From Figures 3–6, it can be deduced that the frequency-selective attenuation of the average reverberation intensity is obviously due to the frequency-selective attenuation of the sound transmission loss.

From Figure 3, the one-way extra transmission attenuation at 1300 Hz for the 060 course due to unknown cause can be estimated to be about 3·3 dB/km. This value is greater than that observed by others [1, 2]. From the figure showing anomalous reverberation attenuation (Figure 6), the one-way extra transmission attenuation at 1300 Hz due to unknown cause can be estimated to be about 2·2 dB/km. It is an average value for all directions, because the average reverberation intensity was obtained by using non-directional explosive sources and an omnidirectional hydrophone.

The Yellow Sea has a vigorous internal wave activity in summer time. Zhou *et al*. [2] proposed an internal wave mechanism to explain the abnormally large sound attenuation at around 600 Hz, which was observed by them in the Yellow Sea. Their theoretical computations show that if one or more internal wave packets exist in shallow water, and each of the packets consists of several solitions with determined wavelength, a significant amount of acoustic energy of lower mode for a certain frequency will transfer to higher modes due to internal soliton packets, i.e., resonant interaction of sound waves with internal solitons causes acoustic mode-coupling, resulting in a resonance-like attenuation.

However, the anomalous attenuation observed in the present paper could not be attributed to the internal wave mechanism. First, under the environmental conditions of our experiments (Figure 1), if the internal wave packets have the characteristic propagating shoreward as indicated in reference [2], the possible direction along which internal wave induced attenuation occurs should be nearly perpendicular to the shoreline, such as the 135 or nearby courses, and should not

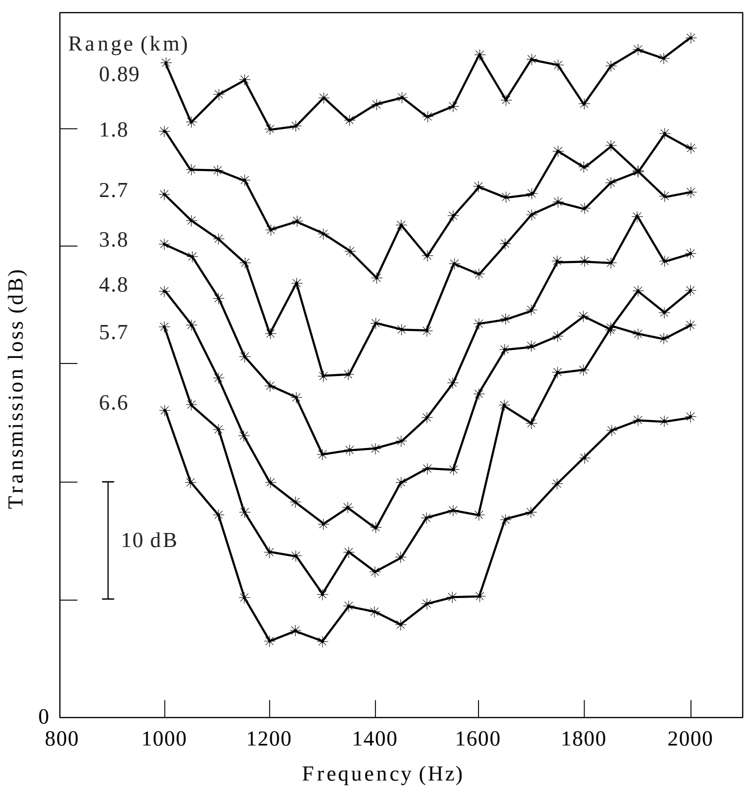

Figure 3. Frequency-selective attenuation of the sound propagation along 060 course. Source depth 7 m, receiver depth 7 m.

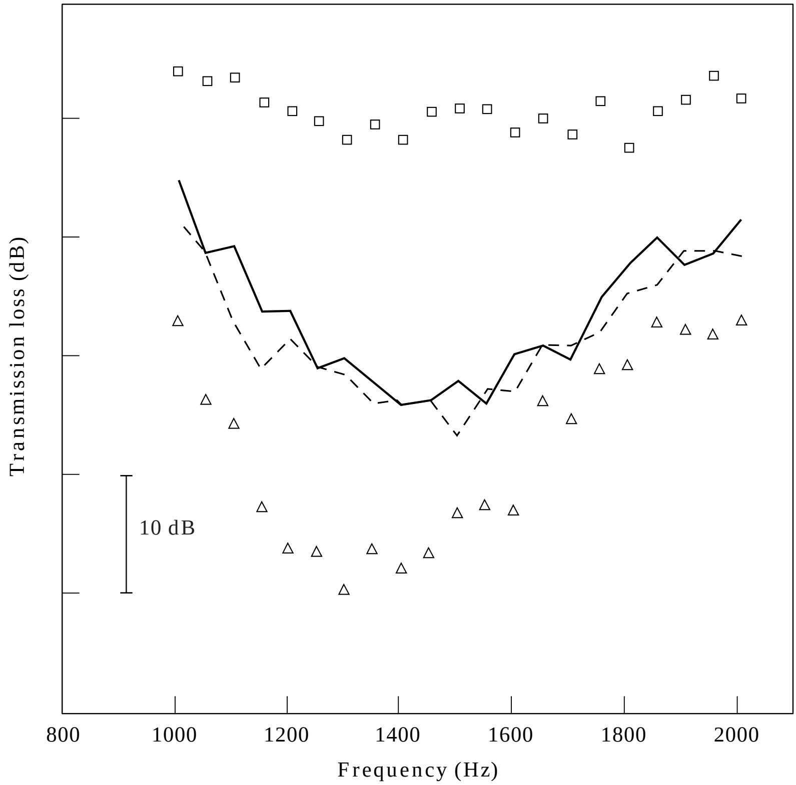

Figure 4. Depth dependence of the transmission loss of 060 course. Range 5·7 km; SD: source depth, RD: receiver depth. – – –, SD = 7 m, RD = 25 m; ——, SD = 25 m RD = 7 m; □□□□, SD = 25 m, RD = 25 m; △△△△, SD = 7 m, RD = 7 m.

be the 060 course. Because the 060 course is almost parallel to the shoreline, along this course the wavelength of the internal wave soliton and the length of packet tend to infinity. Second, Figures 3 and 6 show that the anomalous attenuation of the transmission loss along the 060 course and that of the non-directional average reverberation intensity have a similar centre frequency and bandwidth. It is difficult to explain by any anisotropic mechanism including internal wave in shallow water. Moreover, since there was no anomalous attenuation along the 135 course, it is hardly thinkable that the one-way extra attenuation averaged for all bearings could reach such a large value as 2/3 of the one-way extra attenuation value for a certain direction, provided that the anomalous attenuation was due to a directional internal wave.

The authors believe that the frequency-selective attenuation appearing in our reverberation and propagation experiments is caused by swimbladder resonance of fish (probably, anchovies) living only above the thermocline. This is based on the following observations.

(a) The anomalous attenuation of the transmission loss along the 060 course and that of the reverberation intensity exhibit similar narrow-band resonance characteristics (centre frequency and bandwidth), especially the one-way extra attenuation values estimated respectively from Figures 3 and 6 are of the same order of magnitude. If the frequency-selective attenuation is due to swimbladder bearing fish of the same species with a narrow size distribution, the similarity between the anomalous reverberation and propagation attenuations is easy to understand. Figure 7 shows the distribution of the total length of the Yellow Sea anchovy [4].

(b) The mean length of the Yellow Sea anchovy determined by sampling is 10·6 cm (Figure 7). The resonant frequency of a 10·6-cm anchovy measured by Batzler and Pickwell is 1275 Hz [5]. The resonant frequency of a 10·8 cm anchovy measured by Davies is 1130 Hz [5]. These data show that the centre frequency 1300 Hz of the frequency-selective attenuation observed in this paper corresponds to the mean length of the Yellow Sea anchovy.

(c) From Figure 1, one can find that the 060 course is just in the area where the bluespotted mackerel (a species of fish without swimbladder) seek their food in August every year. The mean length of the bluespotted mackerel is about 51 cm. The main food of the bluespotted mackerel is anchovies. On the contrary, one can notice that the 135 course is not in the area mentioned above.

(d) If fish with swimbladders exist in the water column above the thermocline, they will not affect the sound propagation when both the source and the receiver are below the thermocline. In this case the sound waves, penetrating the thermocline (upward and downward) and suffering more reflections at sea bottom,

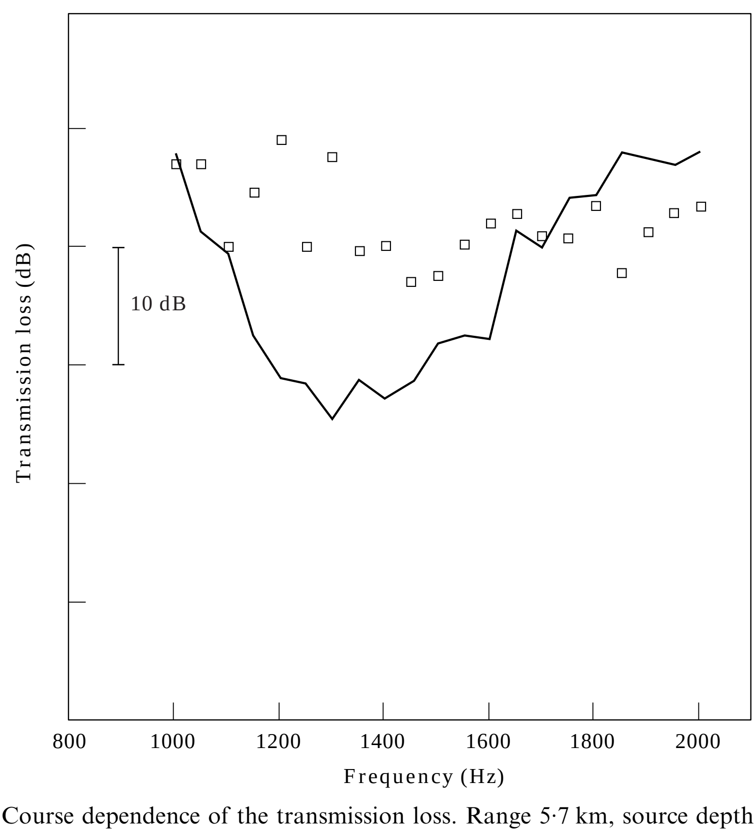

Figure 5. Course dependence of the transmission loss. Range 5·7 km, source depth 7 m, receiver depth 7 m. The solid line shows results for 060 course, the squares represent results for 135 course.

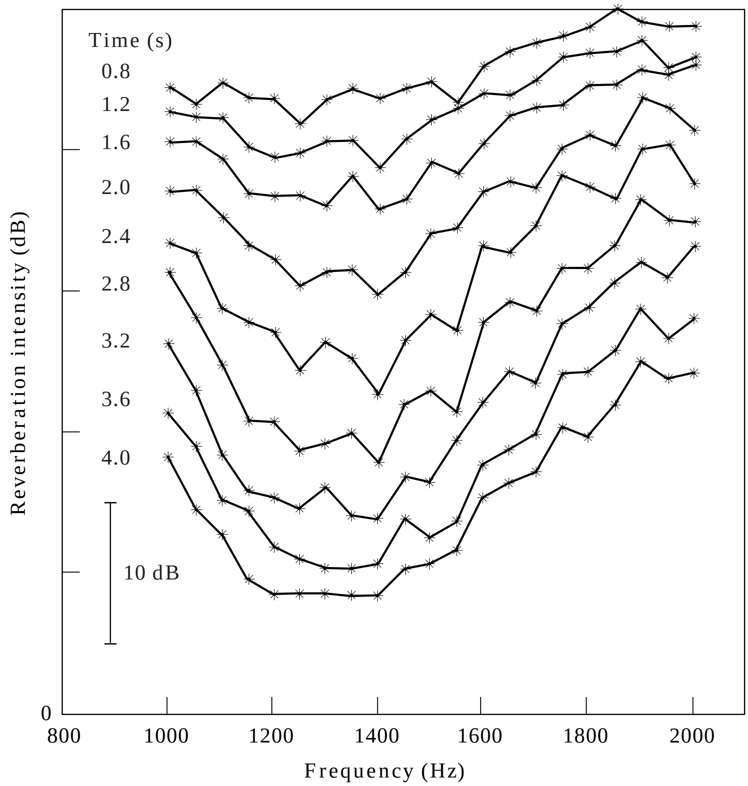

Figure 6. Frequency-selective attenuation of the average reverberation intensity. Source depth 7 m, receiver depth 7 m.

are much weaker than the sound waves propagating only beneath the thermocline. During summer a strong thermocline always exists in the Yellow Sea, and anchovies live only above the thermocline [4]. Consequently, it may result in the following phenomenon: a frequency-selective attenuation occurs when the source and the receiver are above the thermocline, but does not occur when the source and the receiver are below the thermocline.

(e) The number of fish per cubic meter estimated from the extra attenuation (3·3 dB/km) is about $2{\cdot}3 \times 10^{-2}$ (see section 3.2). It seems to be a possible value for the anchovy according to an investigation of anchovy resources in the Yellow Sea for 4 years [4].

(f) Many researchers, who joined in the at-sea experiments in August 1991, remember that they had found a lot of fish swimming around the receiving ship, and a great number of large fish (about 40–50 cm in length) had been hooked up. Although the species of the fish could not be determined with one consent, the appearance of these fish showed that this area did provide the food they needed. In the Yellow Sea the anchovy is the main food of the large and medium-sized fish living in the upper-middle-layer of water [4]. Therefore, the appearance of these fish is important circumstantial evidence for the existence of anchovies in the experimental area.

Weston *et al*. pointed out that the fish echoes and attenuation in shallow water vary diurnally. In the daytime fish swim in shoals, the extra attenuation becomes smaller and echoes stronger; at night fish swim singly or in very small groups, the extra attenuation becomes greater and echoes disappear [1, 6, 7]. The anchovies in the Yellow Sea also swim with diurnal variation, grouping in the daytime and breaking up at night [4]. It is worth stressing that both our propagation experiment along two courses and reverberation experiment were carried out at night. However, diurnal measurements for comparison have not been made.

From Figures 3 and 6 it can be seen that the factor causing the frequency selective attenuation lasted hours during the propagation experiment, and this factor also existed for about 18 h (the separation time between the propagation experiment along the 060 course and the reverberation experiment) later.

3.2. ESTIMATE OF THE MEAN CONCENTRATION OF FISH

It is assumed that the sound wavelength is much greater than the swimbladder sizes and the swimbladder approximates a prolate spheroid. An equation for calculating the ratio of the resonant frequency for a prolate spheroidal bubble f_e to the resonant frequency for a spherical bubble f_o in the case of constant volume of the bubble has been given by Weston [6] (Love [8] noted that this equation is printed incorrectly). Assuming the ratio of the major to the minor semiaxes of the anchovy's swimbladder to be 5, one has $f_e/f_o = 1{\cdot}11$. Then one obtains $f_o = 1170$ Hz as $f_e = 1300$ Hz. The effect of the surface tension on the resonant frequency is negligible, because the surface tension of the anchovy's swimbladder is small [8].

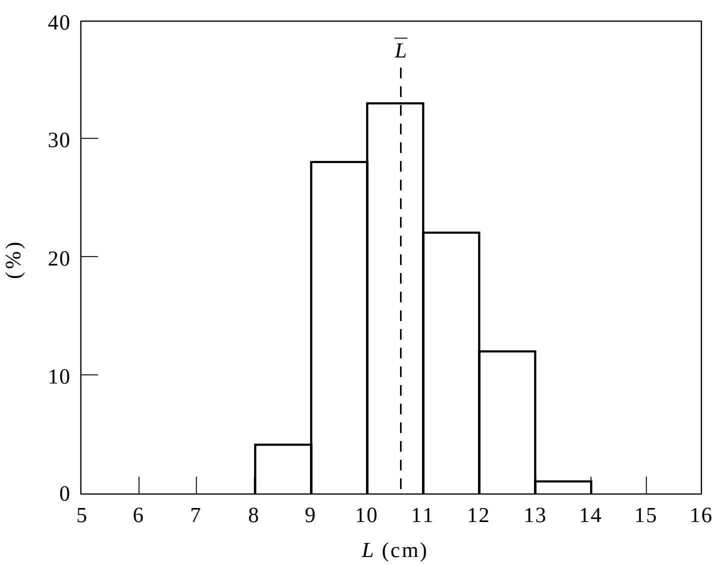

Figure 7. Size distribution of the Yellow Sea anchovy. L represents the total length, and $\bar{L}$ the mean length. The number of sampled fish was 100 (from reference [4]).

The radius of the spherical bubble with the same volume as the swimbladder (a) can be calculated from the following equation [8]:

$$\omega_o^2 a^2 = (3\gamma_a P_o + 4\mu_r)/\rho_{of}, \tag{1}$$

where $\omega_o = 2\pi f_o$, γ_a is the ratio of specific heats of air (the gas in the swimbladder), P_o is the ambient pressure, ρ_{of} is the density of fish flesh, and μ_r is the real part of the complex shear modulus of fish flesh. Substituting $\gamma_a = 1{\cdot}4$, $P_o = 1{\cdot}7 \times 10^5$ N/m^2 (it is assumed that the mean depth of the fish is 7 m), $\rho_{of} = 1050$ kg/m^3 and $\mu_r = 5 \times 10^3$ N/m^2 (this value is obtained by extrapolation using the value of μ_r at 5 kHz and the assumption $\mu_r \propto f_o^2$ [9]) into equation (1), one obtains $a = 3{\cdot}6 \times 10^{-3}$ m.

The Q-factors corresponding to viscous damping, radiation damping and thermal damping for a spherical bubble are

$$Q_{vis} = \omega_o \rho_{of} a^2/(2\xi), \qquad Q_{rad} = \rho_{of} c_w/(\rho_{ow}\omega_o a),$$

$$Q_{th} = \frac{\omega_o^{1/2} a}{3(\gamma_a - 1)} \left(\frac{2\rho_{oa} c_{pa}}{K_a}\right)^{1/2} \left(1 + \frac{2S}{\rho_{of}\,\omega_o^2 a^3}\right)^{-1}, \tag{2}$$

where ξ is a parameter associated with the shear viscosity and bulk viscosity of fish flesh, c_w is the sound velocity in sea water, ρ_{oa} is the density of air, c_{pa} is the specific heat at constant pressure for air, K_a is the thermal conductivity of air, S is the surface tension of swimbladder [8]. Substituting $c_w = 1533$ m/s, $\rho_{ow} = 1026$ kg/m^3, $\rho_{of} = 1050$ kg/m^3, $c_{pa} = 1{\cdot}0 \times 10^3$ J/(kg $\cdot$ K), $\gamma_a = 1{\cdot}4$, $\rho_{oa} = 1{\cdot}3$ kg/m^3, $K_a = 2{\cdot}3 \times 10^{-2}$ J/(m $\cdot$ s $\cdot$ K), $f_o = 1170$ Hz, $a = 3{\cdot}6 \times 10^{-3}$ m, $S = 70$ N/m, $\xi = 13$ Pa $\cdot$ s (where S and ξ for anchovy are given by Love [8]) into equation (2), one obtains $Q_{vis} = 3{\cdot}8$, $Q_{rad} = 59$ and $Q_{th} = 82$.

Using the following definitions and relations:

$$1/Q = 1/Q_{vis} + 1/Q_{rad} + 1/Q_{th},$$

$$\eta_{vis} = 1/Q_{vis}, \qquad \eta_{rad} = 1/Q_{rad}, \qquad \eta_{th} = 1/Q_{th},$$

$$\eta = 1/Q = \eta_{vis} + \eta_{rad} + \eta_{th}, \tag{3}$$

one obtains $\eta_{vis} = 0{\cdot}26$, $\eta_{rad} = 0{\cdot}017$, $\eta_{th} = 0{\cdot}012$, $\eta = 0{\cdot}29$, and $Q = 3{\cdot}4$.

The extinction cross-section at resonance of a spherical bubble in water can be calculated from the following formula [10]:

$$\sigma_e = 4\pi a^2/(\eta\eta_{rad}) = 3{\cdot}3 \times 10^{-2}\ \mathrm{m}^2. \tag{4}$$

If the attenuation coefficient caused by uniformly distributed air bubbles (fish) is known as $K_e = 3{\cdot}3$ dB/km $= 3{\cdot}3 \times 10^{-3}$ dB/m, the mean concentration of fish can be estimated [10]:

$$\bar{n} = K_e/(4{\cdot}34\sigma_e) = 2{\cdot}3 \times 10^{-2}\quad \mathrm{fish/m}^3. \tag{5}$$

The number of fish per cubic meter estimated by Ching and Weston [1] using the value of anomalous attenuation 1·62 dB/km observed at frequency 1·44 kHz is $1{\cdot}33 \times 10^{-2}$. Therefore, the value of anomalous attenuation and the number of fish per cubic meter estimated in this paper are approximately twice as large as Ching and Weston's values.

3.3. VOLUME REVERBERATION DUE TO BACKSCATTERING BY RESONANT SWIMBLADDERS

If we attribute the anomalous attenuation which appeared in our propagation and reverberation experiments to the resonance of swimbladders, a question has to be answered: since the swimbladders can cause strong sound backscattering due to resonance at some frequency, why is there not a peak of resonant scattering at about 1300 Hz in the frequency response of the reverberation intensity? Instead, a dip of resonance attenuation appears.

Assume that fish distribute uniformly in a layer of h (m) in thickness above thermocline. When a source is located above the thermocline and a receiver is near the source, the level of volume reverberation intensity due to backscattering by fish (resonant swimbladders) is [11]:

$$RL_v = 10 \log I_o + 10 \log (2\pi r c_w \tau h \bar{n} \sigma_s / 2) - 2TL_{aa}, \qquad (6)$$

where I_o is the sound intensity at unit range off the source, r is the horizontal distance between the source and the fish yielding backscattering, c_w is the sound velocity in sea water, τ is the length of transmission pulse, $\bar{n}$ is the mean concentration of fish ($2{\cdot}3 \times 10^{-2}$ fish/m^3) estimated from the extra attenuation, σ_s is the backscattering cross-section by single fish, TL_{aa} is the one-way transmission loss from the source to the fish yielding backscattering at a horizontal distance r when both the source and the fish are located above the thermocline.

When a source is located above the thermocline and a receiver is near the source, the level of interface reverberation due to backscattering by the sea bottom is [11]:

$$RL_b = 10 \log I_o + 10 \log (2\pi r c_w \tau \varepsilon / 2) - 2TL_{ab}, \qquad (7)$$

where ε is the bottom scattering coefficient, TL_{ab} is the one-way transmission loss from the source to the sea bottom area yielding backscattering at a horizontal distance r when the source is located above the thermocline. Here it is assumed that the transmission loss in the forward direction is equal to that in the backward direction, i.e., $TL_{ab} = TL_{ba}$ (see Figure 4).

Then, one has

$$RL_v - RL_b = 10 \log (h \bar{n} \sigma_s) - S_b - 2(TL_{aa} - TL_{ab}), \qquad (8)$$

where $S_b = 10 \log \varepsilon$ is the bottom backscattering strength. Figure 4 shows that $TL_{aa} - TL_{ab} \approx 17$ dB at frequency 1300 Hz. The bottom backscattering strength in the experimental area can be estimated to be about -39 dB at 1300 Hz [12]. The calculated radius of the spherical bubble with the same volume as the swimbladder is $a = 0{\cdot}36 \times 10^{-2}$ m, and the calculated value of Q is 3·4 (see section 3.2). Then, one has $\sigma_s = a^2 Q^2 = 1{\cdot}5 \times 10^{-4}$ m^2 [9]. Assuming $h = 14$ m, one can obtain from equation (8) $RL_v - RL_b \approx -38$ dB. This shows that when both the source and the receiver are located above the thermocline, the volume reverberation intensity caused by the resonant swimbladders is very much smaller than the interface reverberation intensity caused by the sea bottom, because TL_{aa} is much greater than TL_{ab}. Consequently, a very obvious dip of resonance attenuation will appear in the frequency response of the reverberation intensity because RL_b and the total reverberation intensity tend to a minimum when TL_{ab} tends to a maximum due to swimbladder resonance.

4. CONCLUSIONS

In the Yellow Sea, when a strong seasonal thermocline exists, anomalous sound transmission loss may occur, not only in the case when both the source and the receiver are located *below* the thermocline as observed in reference [2], but also in the case when both the source and the receiver are *above* the themocline.

Anomalous sound attenuation may be observed not only in experimental results of the transmission loss, but also in experimental results of the reverberation intensity.

The anomalous sound attenuation observed in this paper seems to be caused by swimbladder-bearing fish living above the thermocline (probably, anchovies).

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REFERENCES

1. P. A. Ching and D. E. Weston 1971 *Journal of Sound and Vibration* **18**, 499–510. Wideband studies of shallow-water acoustic attenuation due to fish.
2. J. X. Zhou, X. Z. Zhang and P. H. Rogers 1991 *Journal of Acoustical Society of America* **90**, 2042–2054. Resonant interaction of sound wave with internal solitons in the coastal zone.
3. D. E. Weston 1992 *Journal of Acoustical Society of America* **92**, 3435–3437. Mechanisms of ocean acoustic attenuation: scattering by internal solitons, by sea surface waves, and by fish.
4. Deng Jingyao, Zhao Chuanyin *et al*. 1991 *Marine Fisheries Biology*. Beijing: Agriculture Press (in Chinese).
5. I. E. Davies 1973 *Journal of Acoustical Society of America* **54**, 213–217. Attenuation of sound by schooled anchovies.
6. D. E. Weston 1967 *Underwater Acoustics* Volume 2 (V. M. Albers, editor). New York: Plenum Press. Sound propagation in the presence of bladder fish.
7. D. E. Weston and J. Revie 1971 *Journal of Sound and Vibration* **17**, 105–112. Fish echoes on a long-range sonar display.
8. R. H. Love 1978 *Journal of Acoustical Society of America* **64**, 571–580. Resonant acoustic scattering by swimbladder-bearing fish.
9. L. M. Brekhovskikh 1974 *Ocean Acoustics*. Moscow: Science (in Russian).
10. C. S. Clay and H. Medwin 1977 *Acoustical Oceanography—Principles and Applications*. New York: Wiley.
11. R. J. Urick 1967 *Principles of Underwater Sound for Engineers*. New York: McGraw-Hill.
12. Zhou Jixun, Guan Dinghua, Shang Erchang and Luo Enshen 1982 *Acta Acustica* **7**, 281–289. Long-range reverberation and bottom scattering strength in shallow–water (in Chinese).