13.4; 16.4

Received 1 July 1970

Dorsal-Aspect Target Strength of an Individual Fish

RICHARD H. LOVE

U. S. Naval Oceanographic Office, Washington, D. C. 20390

Experiments are described in which the dorsal-aspect target strengths of a number of individual teleostean fishes of eight species were measured at various frequencies. The results of these experiments indicate that the variations of target strength with frequency are different for fishes in two major teleostean groups, the malacopterygians and the acanthopterygians. These results are combined with results from eight other sources and an empirical equation approximating the dorsal-aspect target strength of an individual fish determined for $0.7 \leq L/\lambda \leq 90$, where L is the fish length and λ is the incident acoustic wavelength. The combined results are compared to similar results for the maximum side-aspect target strength of an individual fish, and curves showing the trend of dorsal-aspect and maximum side-aspect acoustic cross sections of an individual swimbladder-bearing fish are presented for all $L/\lambda \leq 90$.

INTRODUCTION

In most cases where fish are a sonar target of interest the target strength of a fish varies widely with fish length and incident acoustic wavelength. Consequently, a reasonable approximation of the target strength of an individual fish is essential for the design or utilization of such active sonar systems. Reference 1 presents the results of a study on the maximum side-aspect target strengths of individual fish, results which are applicable to forward-looking sonars. The present paper is an extension of Ref. 1, and presents the results of a study on the dorsal-aspect target strengths of individual fish, results which are applicable to downward-looking sonars, i.e., echo sounders. Dorsal-aspect target strengths are of importance because (1) in some cases

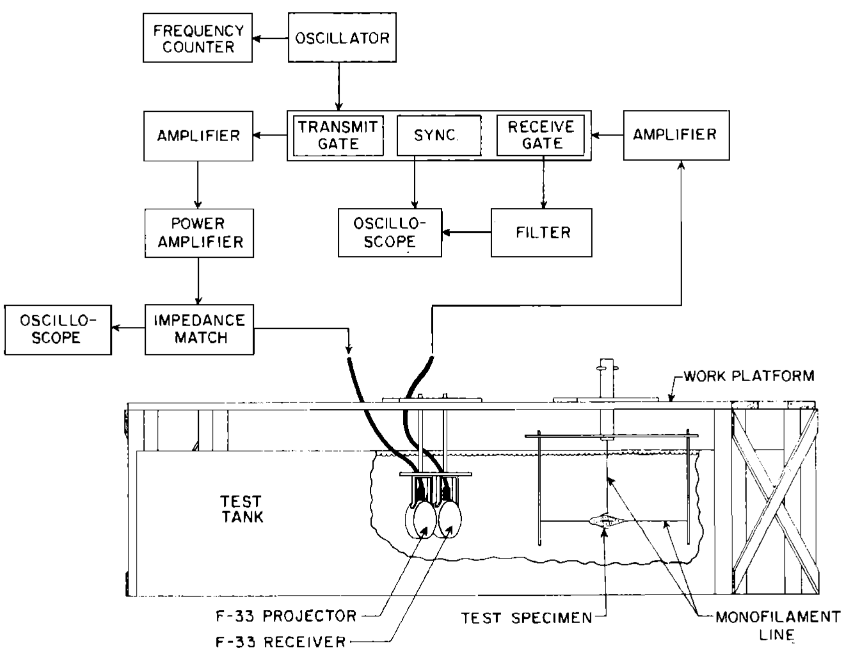

FIG. 1. Experimental setup and electronic block diagram for dorsal-aspect target strength measurements of individual fish.

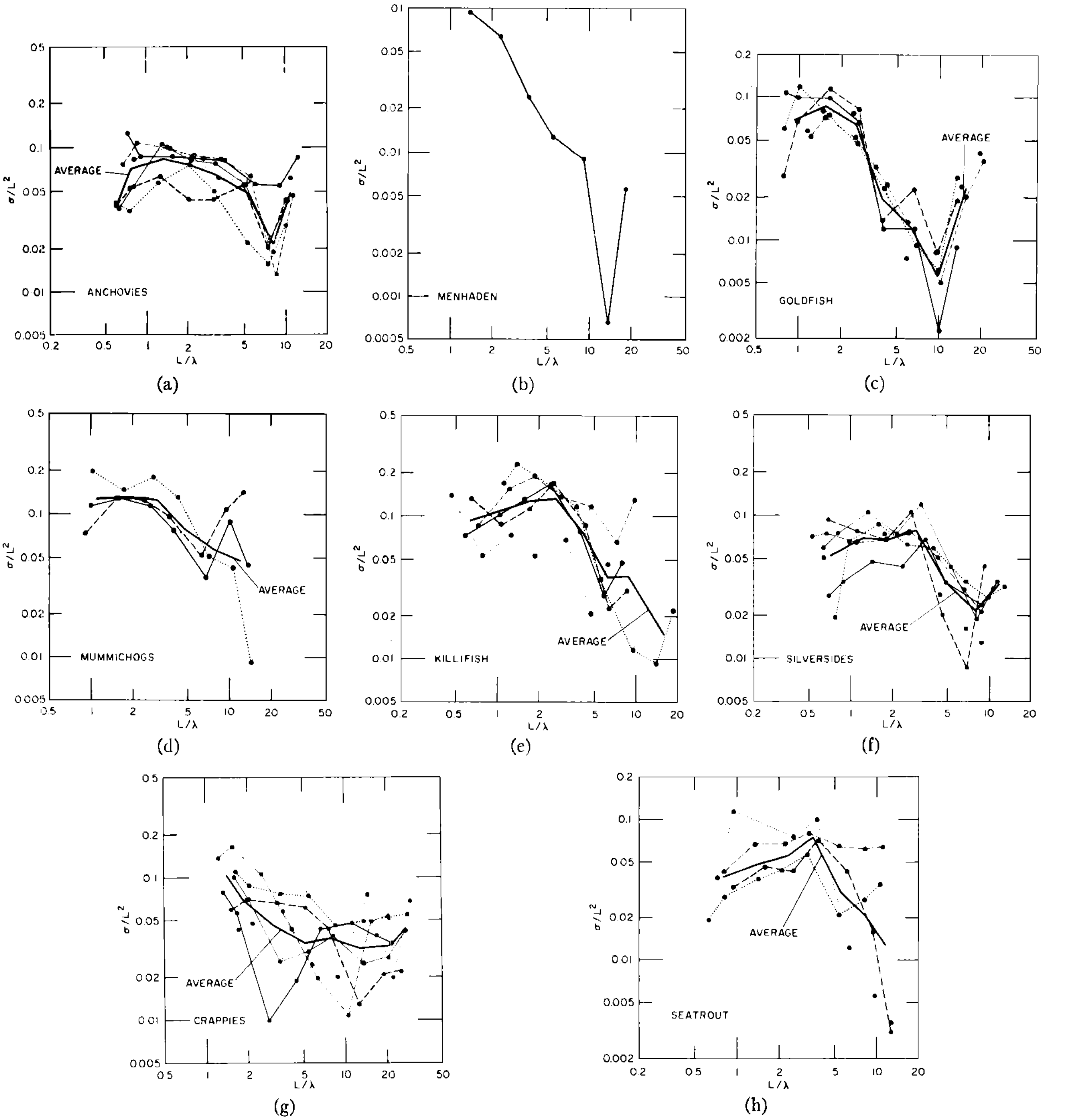

FIG. 2. Individual dorsal-aspect acoustic cross sections for (a) six *Anchoa mitchilli* (bay anchovies); (b) one *Brevoortia tyrannus* (Atlantic menhaden); (c) five *Carassius auratus* (goldfish); (d) three *Fundulus heteroclitus* (mummichogs); (e) five *Fundulus majalis* (striped killifish); (f) six *Menidia menidia* (Atlantic silversides); (g) six *Pomoxis nigromaculatus* (black crappies); and (h) four *Cynoscion nebulosus* (spotted seatrout).

a target detected with a forward-looking sonar can be classified with an echo sounder, and (2) the only acoustic fish detection equipment on many commercial fishing vessels is an echo sounder.

This paper discusses experiments conducted to determine the dorsal-aspect target strengths of small fish as a function of species, size, and incident acoustic frequency. The data obtained are combined with all presently available applicable data into a single nondimensional curve, which can be used to determine the dorsal-aspect target strength of an individual fish. These results are then compared to the results obtained for the side aspect.

I. TARGET-STRENGTH MEASUREMENTS

A. Experimental Method

The experiments were conducted in August and September 1969 in a tank 14 ft in diameter and 3 ft deep. The individual fish were anesthetized and mounted with

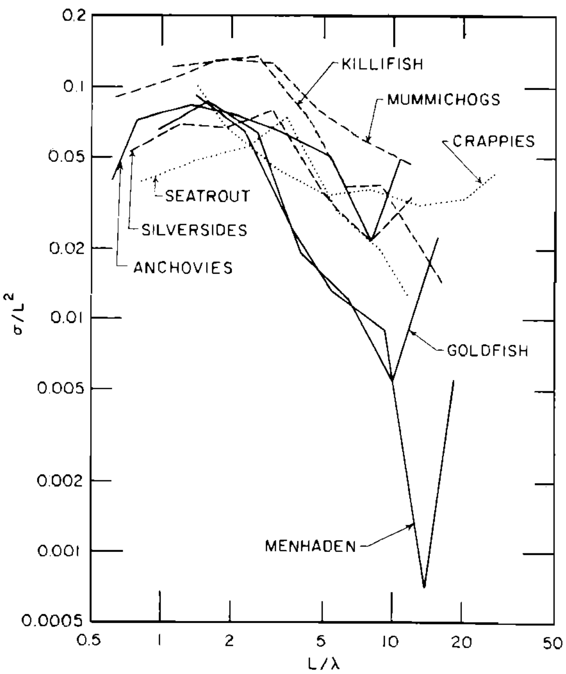

FIG. 3. $\frac{2}{3}$-oct average acoustic cross sections.

monofilament line on a frame and placed at the mid-depth of the tank. As the fish were lowered beneath the water surface, care was taken to remove all air bubbles. The fish were placed at ranges from the transmitting and receiving transducers that were chosen to be great enough so that they were always in the farfield of the transducers and within the 3-dB-down points of the beam, but short enough so that there would no be interference caused by reflections from the frame or the boundaries. The experimental setup and a block diagram of the electronic system utilized are shown in Fig. 1.

The fish tested represented eight species of teleostean fishes from five different orders: *Clupeiformes*, *Cypriniformes*, *Cyprinodontiformes*, *Mugiliformes*, and *Perciformes*. They were six *Anchoa mitchilli* (bay anchovies), one *Brevoortia tyrannus* (Atlantic menhaden), five *Carassius auratus* (goldfish), three *Fundulus heteroclitus* (mummichogs), five *Fundulus majalis* (striped killifish), six *Menidia menidia* (Atlantic silversides), six *Pomoxis nigromaculatus* (black crappies), and four *Cynoscion nebulosus* (spotted seatrout). The fish ranged in length from 1.9 to 8.8 in.

The fish were normally insonified at frequencies of 12, 15, 25, 40, 60, 100, 150, and 200 kHz. The pulselengths were such that all pulses contained at least 10 cycles and were at least 1 ft long. Since the largest fish body depth was 2.8 in., the possibility that the echoes might depend on pulselength was eliminated.

The target-strength determinations were made by utilizing an indirect calibration procedure incorporating reference targets. Calibration of the experimental system was accomplished by substituting thin-walled rubber reference spheres for the fish and comparing the echo level of the target fish to that of the reference target.

B. Present Results

The results of the target-strength measurements for each individual fish are shown in Fig. 2. The data have been presented nondimensionally, using the parameters L/λ and σ/L^2, where L is the fish length, λ the acoustic wavelength, and σ the acoustic cross section of the fish. σ is related to the target strength (T) by

$$T = 10\log(\sigma/4\pi). \tag{1}$$

Average curves for each species are presented in Figs-2(a) and 2(c)–2(h) and are combined in Fig. 3. These curves were determined by calculating the logarithmic average of σ/L^2 and the logarithmic average of L/λ within successive $\frac{2}{3}$-oct bands of L/λ. The more conventional $\frac{1}{3}$-oct bandwidth was not used in this instance because of the few data points within the $\frac{1}{3}$-oct bands.

Examination of Fig. 2 reveals that many of the σ/L^2 vs L/λ curves for the individual anchovies [Fig. 2(a)], goldfish [Fig. 2(c)], and silversides [Fig. 2(f)] resemble the curves of other individuals of the species, as well as the $\frac{2}{3}$-oct average curve for that species. Figure 3 clearly shows that the distinguishing feature of the curves for the anchovies, goldfish, silversides, and menhaden is a sharp dip near $L/\lambda = 10$. The curves for the mummichogs [Fig. 2(d)], killifish [Fig. 2(e)], crappies [Fig. 2(g)], and seatrout [Fig. 2(h)] have no distinguishable features, and the curve for any individual of these species shows no easily discernible relation to most, or all, of the other individuals of its species, or to the $\frac{2}{3}$-oct average curve for that species.

It has been shown previously that in the L/λ range of immediate interest the swimbladder, skeleton, and flesh of a fish all contribute to its acoustic cross section, and it has been assumed that the acoustic interactions of these parts of the fish cause the wide variations in acoustic cross section obtained in this range.[2–4] Also, it has been recently postulated that fish scales can affect a fish's acoustic cross section.[5] In light of this, it is interesting to note that teleostean fishes can be separated into two major groups, the malacopterygians and the acanthopterygians. The malacopterygians, which include the anchovies, menhaden, and goldfish, are the more primitive teleosts, in general having physostomous swimbladders, osseous bone tissue, intermuscular bones, comparatively many vertebrae, fins without spines, and cycloid scales. The acanthopterygians, which include the crappies and seatrout, are the more advanced teleosts, in general having physoclistous swimbladders, osteoid bone tissue, no intermuscular bones, comparatively few vertebrae, fins with spines, and ctenoid scales. The mummichogs, killifish, and silversides belong to intermediate orders, which have characteristics of both malacopterygians and acanthopterygians.[6,7] It is obvious that the malacopterygians and the acanthopterygians have significant structural differences in components that have been shown to contribute to the acoustic cross section of a fish, but it is not possible at this time to say precisely why the malacopterygians and one intermediate species display the characteristic dip in σ/L^2 near $L/\lambda=10$, or why the acanthopterygians and the other two intermediate species have no distinctive σ/L^2 vs L/λ curve.

Since the cause of the apparent difference in the curves for the malacopterygians and the acanthopterygians cannot presently be determined, and since the curves for those fish that belong to intermediate orders may resemble either group, no further attempt has been made to differentiate the species, and the data for all species have been combined and plotted in Fig. 4 using the nondimensional parameters L/λ and σ/λ^2. Combining the data has enabled the average curve shown in this figure to be determined by calculating the logarithmic average of σ/λ^2 and the logarithmic average of L/λ within successive $\frac{1}{3}$-oct bands of L/λ, rather than the $\frac{2}{3}$-oct bands used earlier. It is seen that this average curve is a reasonable estimate of the acoustic cross sections of the fish tested. A mathematical estimate is more useful than the $\frac{1}{3}$-oct average curve, however, and through utilization of the method of least squares a regression line was calculated. The equation of the regression line is

$$\sigma/\lambda^2=0.078(L/\lambda)^{1.57}, \tag{2}$$

with a correlation coefficient of 0.91. Changing the dependent parameter from σ/L^2, which was used earlier, to σ/λ^2 ensured a high correlation coefficient and improved the presentation of the individual data points. This is because, as Eq. 2 shows, σ varies more with L than with λ and the σ/λ^2 vs L/λ presentation essentially presents σ as a function of L for constant λ, whereas the σ/L^2 vs L/λ presentation essentially yields σ as a function of $1/\lambda$ for constant L. Comparison of the target strength values obtained from the regression line and $\frac{1}{3}$-oct average curve shows that the differences are well within 3 dB except for $L/\lambda>25$, where there are very few data points. Hence, the regression line gives a reasonable approximation to the dorsal-aspect acoustic cross section of all the fish tested.

It was thought that the spread in the data could possibly be reduced by introducing a parameter that was more characteristic of the insonified cross section of the fish. Accordingly, $(L\times B)^{\frac{1}{2}}$, where B is the breadth of the fish, was substituted for L, and all the data were reexamined. Although the range of L/B for all the fish was 6–15, the substitution of $(L\times B)^{\frac{1}{2}}$ for L resulted in such a slight reduction in the spread of the data that use of this much less convenient parameter was not warranted.

II. DISCUSSION

All available dorsal-aspect target strength data for complete individual fish have been examined, and all

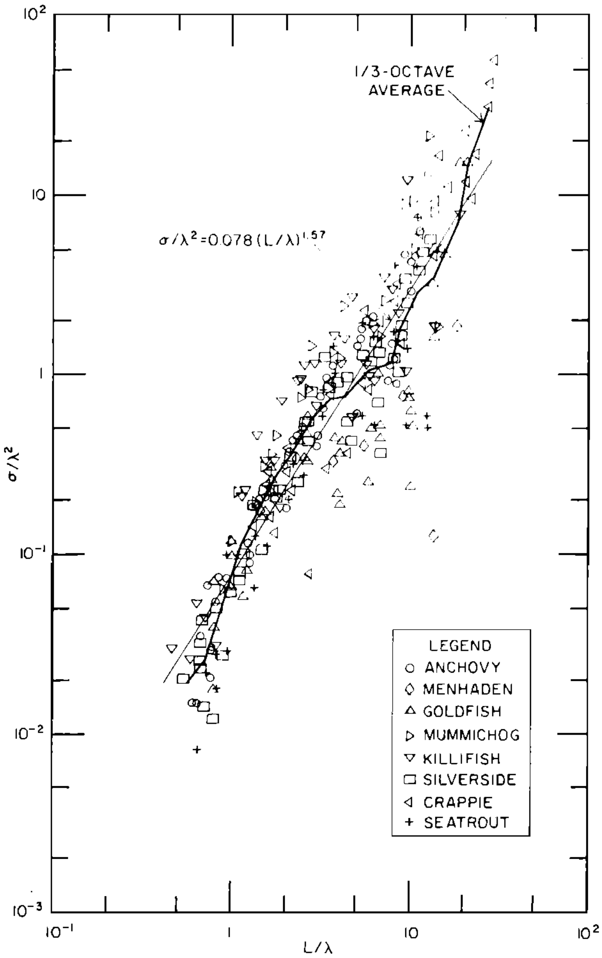

FIG. 4. Dorsal-aspect acoustic cross section of an individual fish as determined from the present data.

data for which fish length, dorsal-aspect target strength or acoustic cross section, and incident acoustic frequency could be determined have been converted into the parameters σ/λ^2 and L/λ. Pertinent data were obtained from eight sources: Jones and Pearce[2]; Volberg[3]; Haslett[4,8]; Hashimoto and Maniwa[9–11]; Yudanov, Gan'kov, and Shatoba[12]; Smith[13]; Midttun and Hoff[14]; and Shishkova.[15] The data from these sources and the present data have been combined in Fig. 5. The data of Fig. 5 were obtained using fish from 16 families in eight different orders: *Clupeiformes*, *Cypriniformes*, *Gasterosteiformes*, *Cyprinodontiformes*, *Mugiliformes*, *Gadiformes*, *Beryciformes*, and *Perciformes*. The fish ranged in length from under 1 in. to just over 1 yd. Some had swimbladders, while others did not. Incident acoustic frequencies ranged from 8 to 1480 kHz.

Utilizing the method of least squares, the equation for the regression line through the combined data is

$$\sigma/\lambda^2=0.043(L/\lambda)^{1.91}, \tag{3}$$

with a correlation coefficient of 0.86. This regression line and the $\frac{1}{3}$-oct average curve for the combined data are

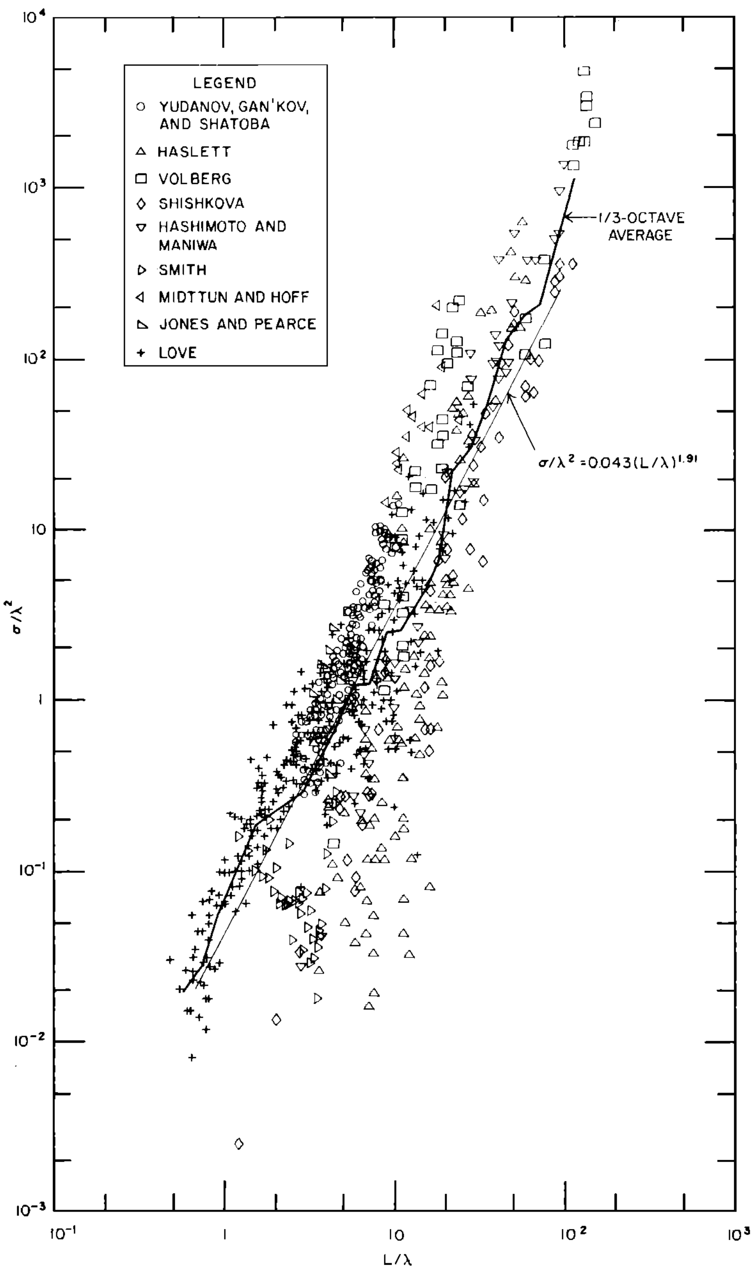

FIG. 5. Dorsal-aspect acoustic cross section of an individual fish as determined from all available pertinent data.

shown in Fig. 5. By combining Eqs. 1 and 3, the dorsal-aspect target strength (T_D) of an individual fish is determined to be

$$T_D = 19.1 \log L + 0.9 \log\lambda - 34.2, \tag{4}$$

where L and λ are in feet and T_D is in decibels relative to a sphere 4 yd in diameter. Comparison of the target-strength values obtained from Eq. 4 and those obtained from the $\frac{1}{3}$-oct average curve shows that the differences are 3 dB or less for $L/\lambda \leq 90$. Therefore, noting the variability in the data, it can be stated that Eq. 4 is a good approximation to the dorsal-aspect target strength of an individual fish for $0.7 \leq L/\lambda \leq 90$.

An equation for the maximum side-aspect target strength (T_S) of an individual fish was given in Ref. 1. However, since its publication, more side-aspect data have been obtained and incorporated, resulting in a slight modification to the equation and extending its L/λ range of applicability. Since, by the nature of an empirical equation, additional data should produce a more accurate equation, only the modified equation is presented:

$$T_S = 22.8 \log L - 2.8 \log\lambda - 32.4, \tag{5}$$

or, in the nondimensional form,

$$\sigma/\lambda^2 = 0.064 (L/\lambda)^{2.28}, \tag{6}$$

for $1 \leq L/\lambda \leq 130$. Again L and λ are in feet and T_S is in decibels relative to a 4-yd-diam sphere. Equation 5 differs from the original equation in Ref. 1 by a maximum of 1.4 dB at $L/\lambda = 100$. The modifying data were obtained from Diercks and Goldsberry,[5] Haslett,[16] and from a short experiment conducted in conjunction with the present dorsal-aspect experiments.

Equations 4 and 5 indicate that the dorsal-aspect and maximum side-aspect target strengths of an individual fish increase approximately as L^2, but that the dorsal-aspect target strength decreases slightly while the maximum side-aspect target strength increases slightly with increasing frequency. This apparent discrepancy can be explained with the aid of Fig. 6, which shows that, in general, the $\frac{1}{3}$-oct average curves of σ/L^2 vs L/λ for both the dorsal and side aspects first decrease and then increase with increasing L/λ. The minimum point for the side aspect occurs near $L/\lambda = 7$, and just over one-half of the data are above this point. The minimum point for the dorsal aspect occurs near $L/\lambda = 14$, and about three-fourths of the data are below this point. It is seen that in neither case does the acoustic cross section either generally increase or decrease with increasing frequency over the complete L/λ range investigated and that the sign of the coefficient of $\log\lambda$ in Eqs. 4 and 5 depends on the distribution of the data points over the L/λ range.

It may now be asked whether a single regression line should be used over the complete L/λ range investigated or whether a pair of regression lines is needed: one to cover the range where σ/L^2 decreases with L/λ, and one to cover the range where σ/L^2 increases with L/λ. If the complete L/λ range is divided in two so that the paired regression lines intersect at the division points, the regression lines obtained for the dorsal aspect are

$$\sigma/\lambda^2 = 0.065(L/\lambda)^{1.58} \tag{7}$$

for $0.7 \leq L/\lambda \leq 14$, and

$$\sigma/\lambda^2 = 0.0030(L/\lambda)^{2.75} \tag{8}$$

for $14 \leq L/\lambda \leq 90$; and for the side aspect

$$\sigma/\lambda^2 = 0.128(L/\lambda)^{1.73} \tag{9}$$

for $1 \leq L/\lambda \leq 7$, and

$$\sigma/\lambda^2 = 0.027(L/\lambda)^{2.54} \tag{10}$$

for $7 \leq L/\lambda \leq 130$. These paired regression lines are compared to the $\frac{1}{3}$-oct average curves and the single regression lines in Fig. 6. Figure 6 shows that, as would be expected, the paired regression lines approximate the $\frac{1}{3}$-oct average curves better than the single regression lines do.

The differences between maximum side-aspect and dorsal-aspect target strengths as determined from the $\frac{1}{3}$-oct average curves, the single regression lines, and the paired regression lines are shown in Fig. 7. It is seen that the maximum side-aspect target strength is always larger than the dorsal-aspect target strength and that the difference between the $\frac{1}{3}$-oct average curves generally increases with increasing L/λ, being approximately 1 dB at $L/\lambda = 1$ and approximately 9 dB at $L/\lambda = 100$. It is seen that the difference between the single regression lines more closely follows this general increase than does the difference between paired regression lines.

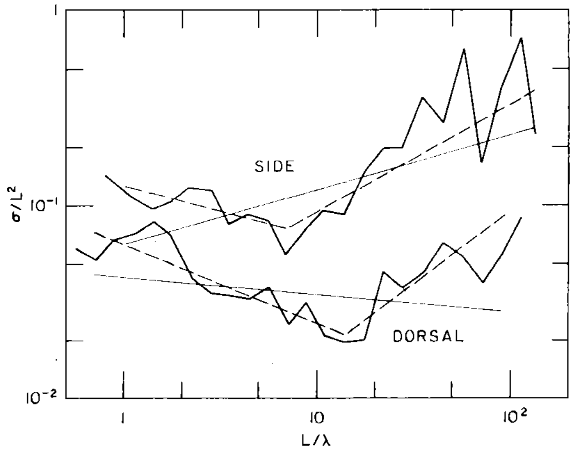

FIG. 6. Comparison of $\frac{1}{3}$-oct average curves with single and paired regression lines for dorsal-aspect and maximum side-aspect acoustic cross sections.

The paired and the single regression lines each have their advantages: the paired lines are slightly more accurate and better illustrate the changes in acoustic cross section with changing L/λ (Fig. 6), and the single lines are more convenient and give a better indication of the difference between dorsal-aspect and maximum side-aspect target strengths (Fig. 7). Given the vari-

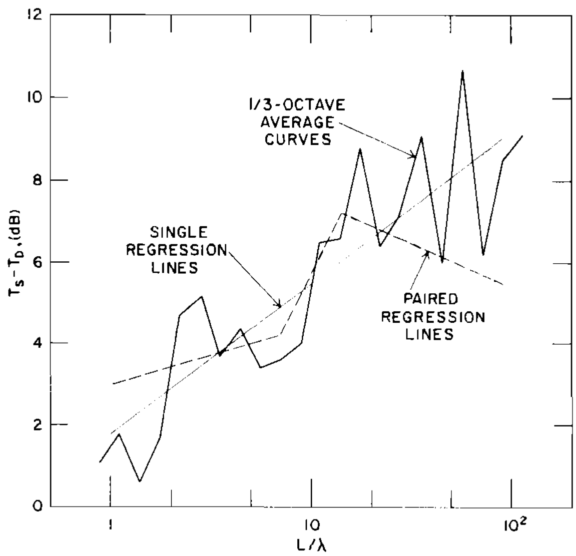

FIG. 7. Differences between maximum side-aspect and dorsal-aspect target strengths calculated using the $\frac{1}{3}$-oct average curves and the single and paired regression lines.

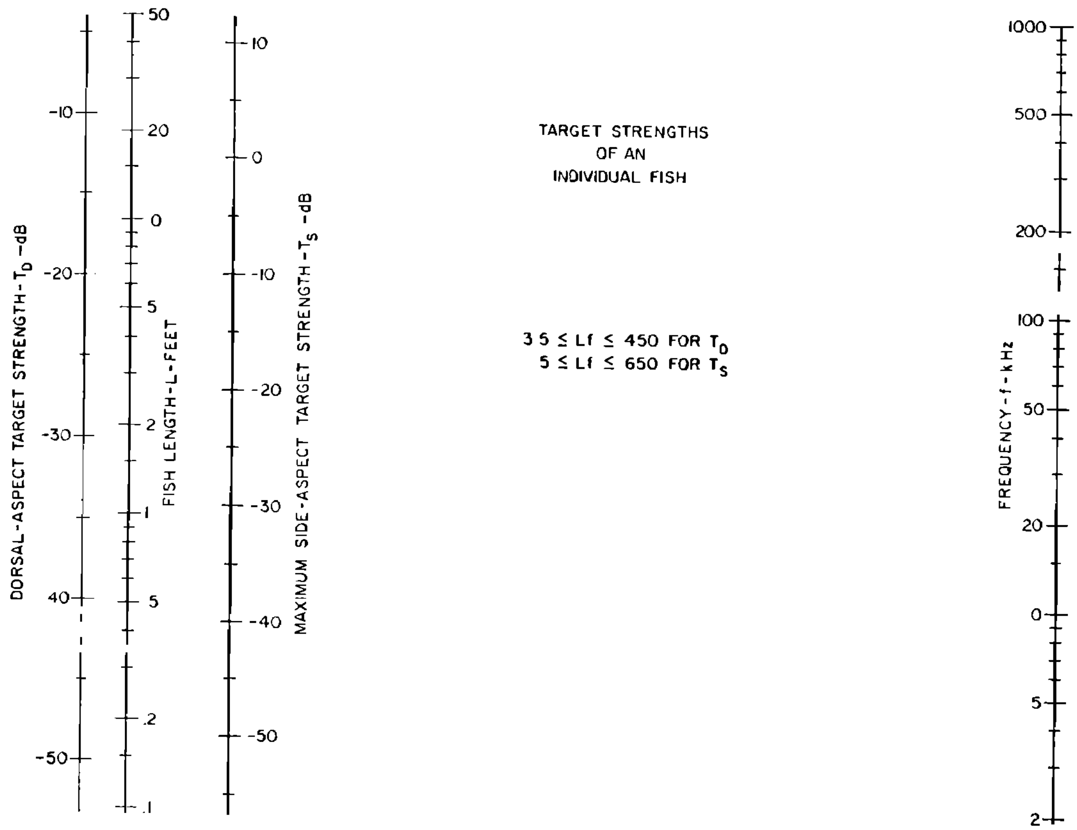

FIG. 8. Nomogram for calculating the dorsal-aspect and maximum side-aspect target strengths of an individual fish over the ranges $3.5 \leq Lf \leq 450$ for dorsal aspect and $5 \leq Lf \leq 650$ for side aspect.

ability in the data and the relative merits of the paired and single regression lines, it is felt that, when an estimate of target strength is required, the more convenient single regression lines should be utilized. Hence, Fig. 8 is a nomogram for the dorsal-aspect and maximum side-aspect target strengths of an individual fish based on the single regression lines. However, when the trend of acoustic cross section over a range of L/λ is required, it is best to use the paired regression lines.

An estimate of the acoustic cross section of an individual swimbladder-bearing fish for $L/\lambda \leq 90$ may be obtained by assuming that only the contribution of the swimbladder is important for L/λ values somewhat below one. Andreeva and Chindonova[17] give equations for the determination of swimbladder resonant frequency and acoustic cross section, and Ref. 1 gives results utilizing these equations assuming a depth (D) of 20 ft, a ratio of fish length to equivalent spherical swimbladder radius (R) of 20, and a quality factor of resonance (Q) of 5. For frequencies somewhat above and below resonance, equations given by Weston[18] for an ideal spherical bubble, volumetrically equal to the fish's swimbladder, can be used to approximate the fish's acoustic cross section. Combining the results from the equations of Andreeva and Chindonova and of Weston with the paired regression lines, curves showing the trend of acoustic cross section with fish length and acoustic wavelength are drawn in Fig. 9 for all $L/\lambda \leq 90$. Because of the nature of the nondimensional parameters used, Fig. 9(a) shows the variation of acoustic cross section with fish length for a given incident frequency, and Fig. 9(b) shows the variation of acoustic cross section with acoustic wavelength for a given fish size.

III. SUMMARY

An empirical equation has been developed that approximates the dorsal-aspect target strength (T_D) of an individual fish in the L/λ range of interest for most sonar applications. This equation was developed by combining the nondimensionalized results from the present experiments with results from eight other sources. The results obtained in the present experiments indicate the possibility that more primitive teleostean fishes have a σ/L^2 vs L/λ curve, which is unlike that for more advanced teleostean fishes. By comparing the results obtained for dorsal-aspect target strength to similar results for maximum side-aspect target strength (T_S), it was found that T_S is greater than T_D over the common range of data of $1 \leq L/\lambda \leq 90$, and that the difference increases with increasing L/λ. It was also found that, in general, over the L/λ range

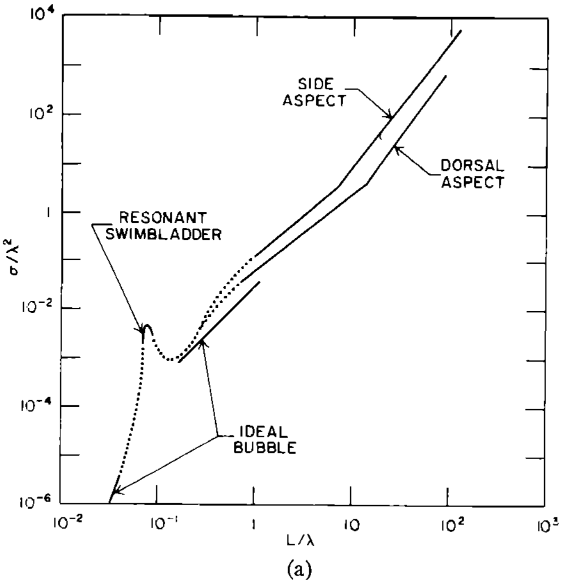

FIG. 9. Estimated dorsal-aspect and maximum side-aspect acoustic cross sections of an individual bladder fish, assuming $D=20$ ft, $Q=5$, and $R/L=1/20$. (a) σ/λ^2 vs L/λ; (b) σ/L^2 vs L/λ.

of the data, both the dorsal-aspect and maximum side-aspect acoustic cross sections decrease as L/λ increases to approximately 14 and 7, respectively, and then both increase as L/λ increases further.

ACKNOWLEDGMENTS

The author thanks W. L. Pugh and J. L. Dunn, Jr., for their assistance in collecting, mounting, and identifying the specimens used in the experiment.

[1] R. H. Love, "Maximum Side-Aspect Target Strength of an Individual Fish," J. Acoust. Soc. Amer. **46**, 746–752 (1969).

[2] F. R. Harden Jones and G. Pearce, "Acoustic Reflection Experiments with Perch (*Perca fluviatilis* Linn.) to Determine the Proportion of the Echo Returned by the Swimbladder," J. Exp. Biol. **35**, 437–450 (1958).

[3] H. W. Volberg, "Target Strength Measurements of Fish," Straza Industries, El Cajon, Calif., Rep. R-101 (1963).

[4] R. W. G. Haslett, "Acoustic Backscattering Cross Sections of Fish at Three Frequencies and their Representation on a Universal Graph," Brit. J. Appl. Phys. **16**, 1143–1150 (1965).

[5] K. J. Diercks and T. G. Goldsberry, "Target Strength of a Single Fish," J. Acoust. Soc. Amer. **48**, 415–416 (L) (1970).

[6] L. Bertin and C. Arambourg, "Super-ordre des téléostéens," in *Traité de zoologie Volume 13, Agnathes et poissons*. P.-P. Grassé, Ed. (Masson et Cie., Paris, 1958), pp. 2204–2500.

[7] L. S. Berg, *Classification of Fishes, both Recent and Fossil* (J. W. Edwards, Ann Arbor, Mich., 1947).

[8] R. W. G. Haslett, "Determination of the Acoustic Back-scattering Patterns and Cross Sections of Fish," Brit. J. Appl. Phys. **13**, 349–357 (1962).

[9] T. Hashimoto and Y. Maniwa, "Ultrasonic Reflection Loss of Fish Shoal and Characteristics of the Reflected Wave," Tech. Rep. Fishing Boat No. 6 (1955), pp. 113–139 [Engl. transl.: Ministry of Agriculture, Fisheries and Food, Fisheries Lab., Lowestoft, England (1957)].

[10] T. Hashimoto and Y. Maniwa, "Study of Reflection Loss of Ultrasonic Millimeter Wave on Fish-Body," Tech. Rep. Fishing Boat No. 8 (1956), pp. 113–118 [Engl. transl.: Ministry of Agriculture, Fisheries and Food, Fisheries Lab., Lowestoft, England (1957)].

[11] T. Hashimoto and Y. Maniwa, "Study of Reflection Loss of Ultrasonic Millimeter Wave on Fish-Body (2)," Tech. Rep. Fishing Boat No. 9 (1956), pp. 165–173 [Engl. transl.: Ministry of Agriculture, Fisheries and Food, Fisheries Lab., Lowestoft, England (1957)].

[12] K. I. Yudanov, A. A. Gan'kov, and O. E. Shatoba, "Reflection of Sound by Commercial Fish of the Northern Basin," Rybn. Khozy. **12** (1966), pp. 57–60 [Engl. transl.: Clearinghouse for Fed. Sci. Tech. Inform. Doc. TT-67-61940].

[13] P. F. Smith, "Further Measurements of the Sound Scattering Properties of Several Marine Organisms," Deep-Sea Res. **2**, 71–79 (1954).

[14] L. Midttun and I. Hoff, "Measurements of the Reflection of Sound by Fish," Rep. on Norwegian Fishery and Marine Investigations 13, No. 3, Bergen, Norway (1962).

[15] E. V. Shishkova, "Study of Acoustical Characteristics of Fish," in *Modern Fishing Gear of the World-2*, Technical Staff of Fishing News International and Fishing News (Books) Ltd., Ed. (Fishing News Ltd., London, 1964), pp. 404–409.

[16] R. W. G. Haslett, "The Target Strengths of Fish," J. Sound Vib. **9**, 181–191 (1969).

[17] I. B. Andreeva and Yu. G. Chindonova, "On the Nature of Sound Scattering Layers," Okeanologiya **4**, 112–123 (1964) [Engl. transl.: Joint Publ. Res. Serv. **24**, 274 (1964)].

[18] D. E. Weston, "Sound Propagation in the Presence of Bladder Fish," in *Underwater Acoustics*, V. M. Albers, Ed. (Plenum, New York, 1967), Vol. 2, Chap. 5, pp. 55–88.