ACOUSTIC REFLEXION EXPERIMENTS WITH PERCH (*PERCA FLUVIATILIS* LINN.) TO DETERMINE THE PROPORTION OF THE ECHO RETURNED BY THE SWIMBLADDER

By F. R. HARDEN JONES
Fisheries Laboratory, Lowestoft
and G. PEARCE
Kelvin and Hughes Ltd., Barkingside, Essex

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INTRODUCTION

Cushing & Richardson (1955) found that the echo returned by artificial swimbladders hung alongside dead cod suggested that from 35 to 70% of the echo energy returned by a normal fish would come from the swimbladder. However, they were not able to measure the amount of energy reflected from a single fish with and without its swimbladder. Laboratory experiments have been carried out to look further into this matter, their immediate purpose being an attempt to determine, under controlled conditions, the contribution of the swimbladder to the strength of an echo returned by a fish.

METHOD

The experiments were carried out at Kelvin and Hughes Ltd., Barkingside, Essex, in an indoor freshwater tank of dimensions 6 m. long, 3 m. wide and 3 m. deep. The amplitude of the echo returned by a freshly killed fish suspended in the tank was measured before and after the removal of the gas from the swimbladder. The effect of substituting a false swimbladder after the removal of the real one was also examined. The transmitting and receiving transducers and the target system were placed on the long axis of the tank. The transducer system was 1·5 m. from one end of the tank and the distance between the transducers and the fish 3·3 m.

(i) *The choice of the fish for a target.* The experiments could only be carried out on dead fish of a size consistent with the physical limitations of the whole system, which are discussed later. It was necessary to select a freshwater fish about 20 to 30 cm. in length which would not lose any appreciable amount of gas from the swimbladder for 2–3 hr. after death. The perch, *Perca fluviatilis*, seemed the best choice, since it is hardy, is easily kept in captivity, and has a well-developed closed swimbladder occupying about 7% of its total volume (Plattner, 1941; Jones, 1951) which does not lose any significant amount of gas during the first few hours after death.

Twenty perch, whose lengths ranged from 16·5 to 24·0 cm., netted in 2 to 3 m.

of water, were obtained from dealers and kept in excellent condition in tanks until required.

(ii) *Electro-acoustic apparatus.* The electro-acoustic equipment consisted of a valve transmitter from a standard Kelvin-Hughes MS. 28 echo sounder, two MS. 28 transducers acting as the projector and hydrophone units, and a Cossor Model 1049 Mk. III oscilloscope.

The valve transmitter gave an electrical output of 400 W. in pulses, the lengths of which could be chosen to be 0·5, 1·0 or 2·5 msec. as required. The pulse repetition rate was 200 per minute.

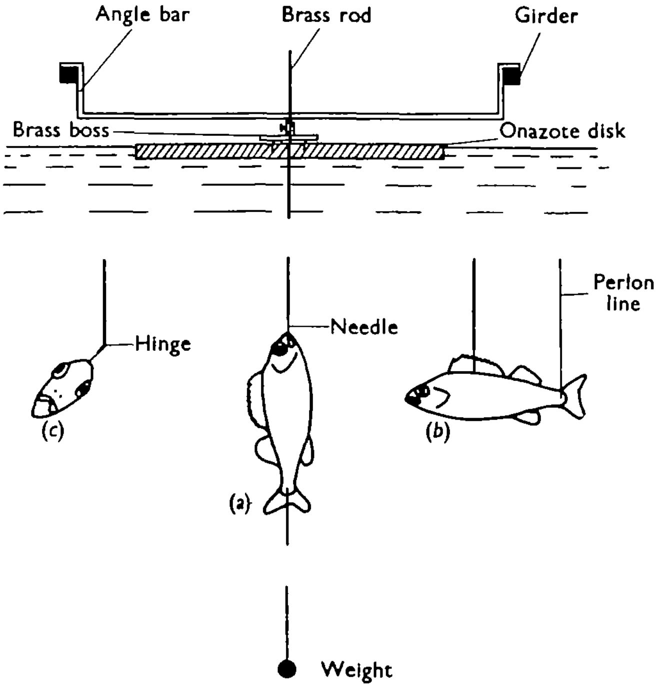

Fig. 1. Diagram to show the method used to suspend the fish in the tank.

The MS. 28 transducers acting as projector and hydrophone were operated at their resonant frequency of 30 kc./s. The radiating face of each was of dimensions 14·5 × 9 cm. (approximately $3\lambda \times 2\lambda$ at 30 kc./s.). These units were mounted one above the other with their longer sides adjacent, so that the centre of this projector-hydrophone system was 1·5 m. below the water surface. This system was fixed rigidly relative to the sides of the tank. The projector was connected to the MS. 28 echo sounder valve transmitter; such a system produced an acoustic output of 160 W. The hydrophone was connected to the amplifier input of the oscilloscope, and the received signals were displayed on the cathode-ray tube in A-scope presentation.

(iii) *Target suspension.* The target was held in mid-water on a straight brass rod 0·16 cm. in diameter as shown in Fig. 1. The rod was secured by a grub screw to a brass boss locked by spikes to a disk of 60 cm. diameter floating on the water surface. This disk was made of 'Onazote', a rigid foamed ebonite material in which the individual air cells are isolated from one another. The free end of the rod ran through a slot in an angle bar clamped to girders running across the top of the tank. This arrangement allowed the target to be kept at a constant depth, and also allowed the vertical axis of the target suspension system to be fixed rigidly with respect to the projector-hydrophone system. The floating disk, boss and rod could be turned to rotate the target relative to the transducers, the angle of rotation being read from a degree scale marked on the 'Onazote' disk.

The target fish was impaled on the point of a darning needle soldered to the end of the brass rod. The needle was run into the skull or dorsal flesh of the fish as shown in Fig. 1 according to whether rotation was to be carried out about the longitudinal or vertical axis of the fish. The needle was held firmly into the fish by a loop of 'Perlon' of diameter 0·05 cm. through the body. This thread was then passed through the eye of the needle and was drawn tight. This method of suspension proved very successful and the fish followed the rotation of the 'Onazote' disk well. In the experiments involving rotation about its longitudinal axis the fish was kept vertical in the water by means of a small weight attached to the tail as shown in Fig. 1*a*. During rotation about the vertical axis of the fish it was necessary to support the tail after emptying the swimbladder. This was done by a 'Perlon' line (Fig. 1*b*) running up to a slit cut in the 'Onazote' disk. In some experiments involving rotation about the vertical axis the fish was fitted at an angle to the vertical to see what effect this would have on the strength and pattern of the returned signals. This was done by making a small hinge in the brass rod immediately before the point at which the darning needle was soldered to it (Fig. 1*c*). The hinge was held at any required angle of tilt by a low melting-point solder, adjustment being made with an electric soldering iron with the hinge clear of the water but the fish below the surface.

(iv) *False swimbladders*. The false swimbladders used throughout the experiment were made of 'Onazote'. This has an acoustic reflexion coefficient at 30 kc./s. of the order of 0·95. In the first experiments blocks of 'Onazote' were modelled into the shape of a cigar similar to that of the swim bladder, but in the later ones it was found more satisfactory to cut cylindrical cores from blocks with a cork borer of suitable diameter and then to cut these down to the required length.

(v) *Experimental procedure*. The fish were killed as required by prolonged immersion in 10% urethane. After an hour the fish, which was now floating in the water, was removed and quickly attached to the supporting rod and 'Perlon' lines. This took 3–4 min. and the fish was kept moist while this was done. The fish was then lowered into the water, care being taken to see that no air bubbles remained trapped within the mouth or under the gill covers. The rod and attached brass boss were locked on to the 'Onazote' disk and the rod engaged into the slot in the clamped angle bar. A series of readings was then taken.

The fish was lined up so that a tail-on or dorsal surface-on position conformed to the zero of the degree scale marked upon the 'Onazote' disk. For this position, the amplitude of the received signals as displayed upon the oscilloscope was measured. The target system was then slowly rotated through a known angle and when the system was stationary the amplitude of the received signal was again measured. This was repeated at equal angular intervals for a 360° rotation of the fish. During rotation about the longitudinal axis measurements of the returned signal were made every 10° during anticlockwise rotation. In the experiments involving rotation about the vertical axis measurements were made every 3° during anticlockwise rotation.

After a complete rotation of 360° the rod, boss, disk and fish were disengaged from the angle bar and brought to the side of the tank and the fish was raised to a few centimetres below the surface. This was done as a check and control measure against any variations that might occur due to disturbance of the positioning of the fish when it was brought to the surface to empty the swimbladder. The system was then returned to its previous position and a second complete set of measurements made. The fish was again brought to the side of the tank and the left side cut through with the fish under water to release the gas from within the swimbladder. Every precaution was taken to ensure that no gas remained within the body of the fish. Another set of measurements was made, the target system was again moved to the side of the tank and up to the water surface, back to the centre of the tank and the observations were repeated. Next, a false swimbladder made of 'Onazote' and of approximately the same dimensions as the normal one was slipped into the body of the fish and two further sets of measurements made. Finally one series was made with the false swimbladder alone. A complete experiment thus gave duplicates of the polar diagrams for the fish with the swimbladder full, with the swimbladder empty, the fish with a false swimbladder and one of the false swimbladder alone. Experiments were done with nine fish rotated about the longitudinal axis and five fish rotated about the vertical axis. All these experiments were done using a pulse length of 0·5 msec. In each main set of experiments one was repeated with a pulse length of 1·0 msec.

(vi) *Precautions and limitations of the measurements.* The possible sources of error due to the acoustic limitations of the system can be of importance, and care was therefore taken to reduce these errors to a minimum.

(*a*) The target must be uniformly irradiated by the sound energy. Precautions were therefore taken to ensure that the measurements were carried out within the Fraunhofer region of the transducer sound field, and that the fish occupied part of this region where the sound field was uniform. Measurement showed that the fish was always within a sphere of diameter 30 cm. within which the sound intensity level did not vary by more than 1·0 db.

(*b*) The chief disadvantage of working in what is effectively such a small tank is the reverberation produced due to successive reflexions within the tank. If the target echoes are well above the reverberation level, then the interference between the target echoes and reverberations will not affect the magnitude of the target echoes to any significant extent. If, however, the two signals are of the same order of magnitude, then the wave interference can obviously produce anomalous results.

In these experiments, the amplitudes of largest signals were 20–23 db., i.e. about sixteen times, above the reverberation level. The smallest signals were, however, of the same order of magnitude. This effect was reduced to a large extent by arranging the target system in position so that its echo occurred in a 'hole' in the reverberation pattern. The existence of such a 'hole' was observed on the oscilloscope, since the energy received by the hydrophone, for any one transmitted pulse, obeys a certain intensity-time law. Consequently, the oscilloscope trace displaying the received signals does not change from one transmission to the next. At the particular time corresponding to the 'hole' the reverberation level was 10 db. (i.e. one-third of the amplitude) below the smallest signal to be measured. This 'hole' corresponded to no signal at the transducer face, rather than to destruction interference of two or more larger signals, since moving the transducer system backwards and forwards a few wave-lengths did not produce any change in the signal level within the 'hole', and produced the correct movement of the 'hole' with respect to time.

(*c*) Care must be taken to ensure that no unwanted air is contained anywhere upon the target system. No air bubbles were allowed to remain within the mouth of the fish, or to become entrapped after the swimbladder was split and emptied, and the suspension system was wiped with detergent before immersion to remove air bubbles. The fish was only removed from the water when it was attached to the brass rod. It seemed unlikely that such a short exposure to air would dry the skin of the fish to such an extent as to trap a surface film of air on its return to water and prevent it from being completely rewetted.

(*d*) The shortest pulse available, 0·5 msec., was sufficiently long for the fish to be completely enveloped within it. Consequently, the echo received was characteristic of the fish as a whole, and could not be analysed into echoes from individual portions of the target. In any case, with the transducers used it is not possible to produce at 30 kc./s. a pulse sufficiently short to allow such an analysis to be made.

At intervals throughout the experiment the output from the projector was monitored. It was found to be constant to within $\pm 0{\cdot}8$ db. over a long period and to within much less for short periods. The over-all precision of any one series of measurements is estimated from a consideration of the possible errors to be $\pm 1{\cdot}0$ db.

As a check upon the accuracy of the measurements, an experiment was performed using as a target a hollow thin-walled sphere of diameter 20 cm. The target strength of this was measured and was compared to the calculated target strength, both these values being the strengths relative to a sphere of 2 m. radius. The measured target strength was $-24{\cdot}7$ db, and the calculated target strength was $-25{\cdot}8$ db. The discrepancy between these figures is not greater than expected.

RESULTS

(i) *Rotation about the longitudinal axis.* Two sets of measurements have been taken as representative of the whole nine sets which were made. The results corresponding to these two sets are shown in Figs. 2 and 3. The duplicate sets of readings agree

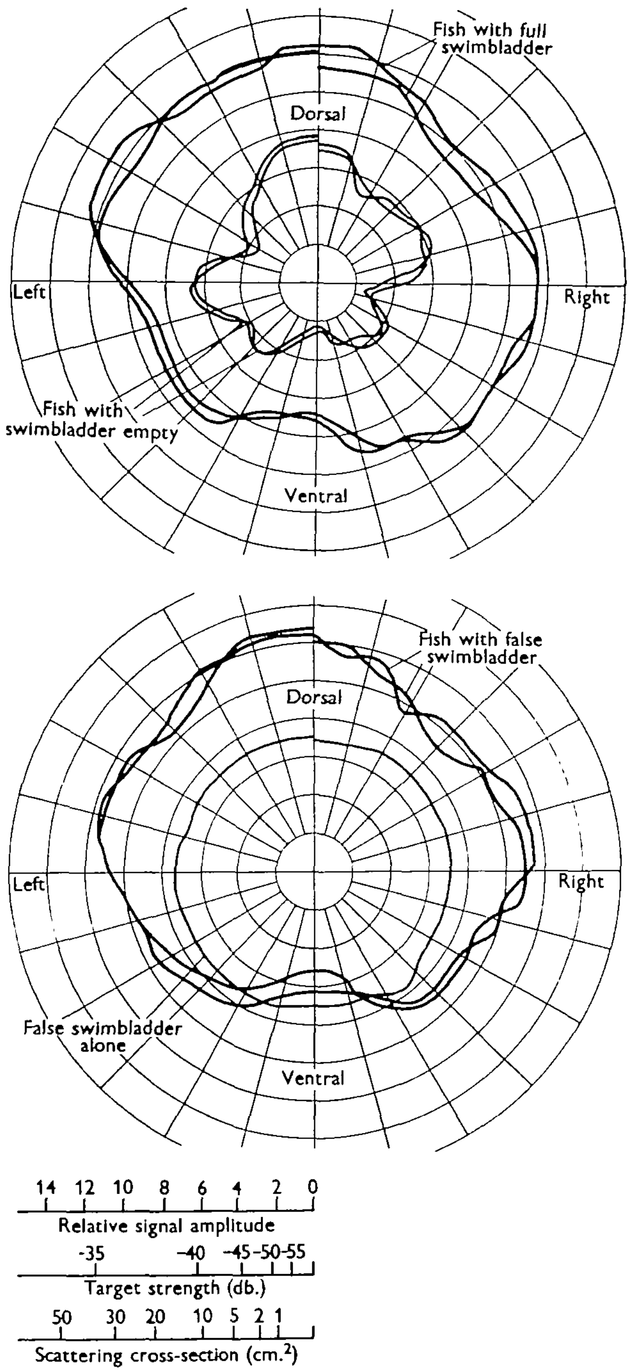

Fig. 2. Polar diagrams of relative signal amplitude, target strength and scattering cross-section obtained by rotating a fish about its longitudinal axis. Fish no. 6, 21·6 cm. long. False swim-bladder 6 cm. long, 1·2 cm. diam., cylindrical, prepared with cork borer. The polar co-ordinate scales have been put below the diagrams to avoid superimposition.

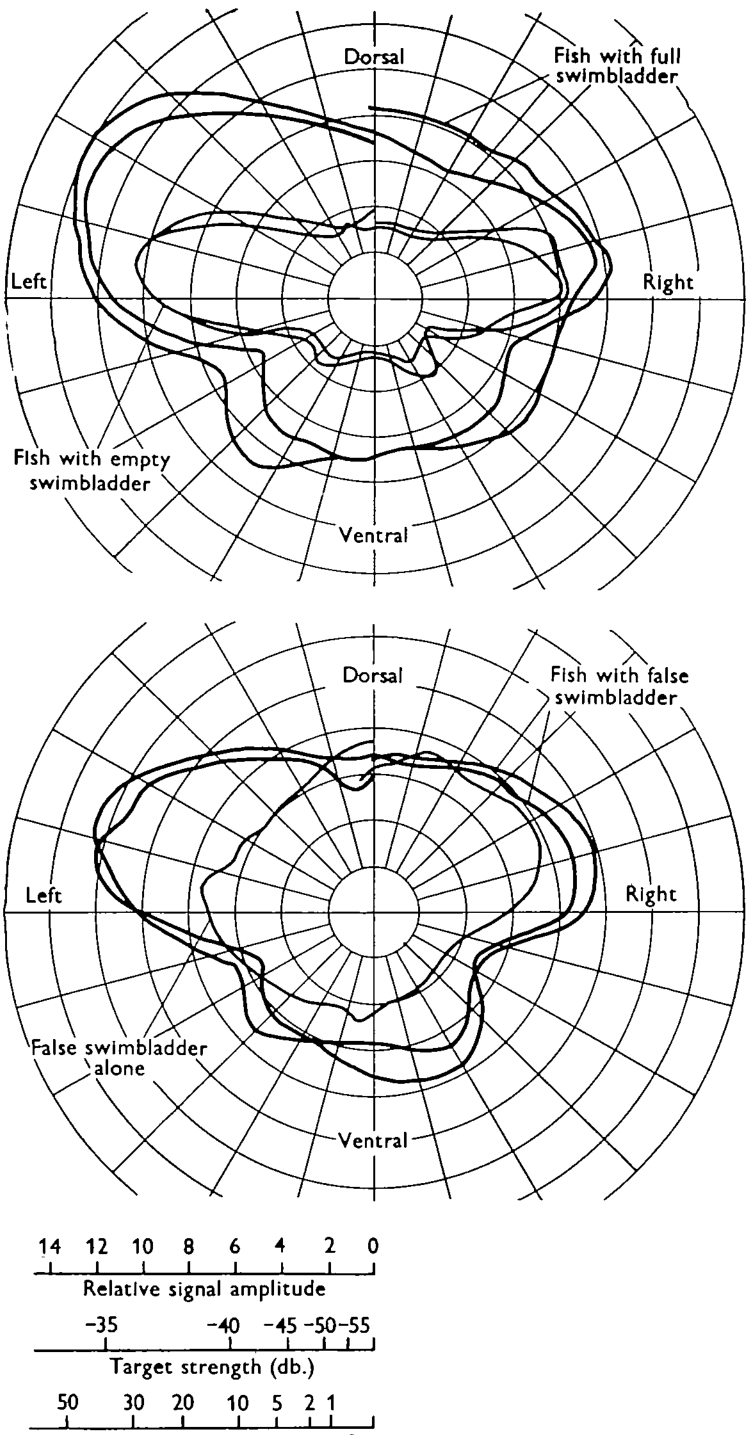

Fig. 3. Polar diagrams of relative signal amplitude, target strength and scattering cross-section obtained by rotating a fish about its longitudinal axis. Fish no. 4, 19·0 cm. long. False swimbladder 4 cm. long, max. diam. 1·2 cm., roughly cigar-shaped, cut by hand. The polar coordinate scales have been put below the diagrams to avoid superimposition.

well with one another and there is a marked reduction in the strength of the echo returned by the fish after the swimbladder is emptied. The echo signal was restored very closely to its original value by putting a piece of 'Onazote' into the space previously occupied by the swimbladder. In general, the pattern obtained by rotating the fish about the longitudinal axis approached one or other of the two shown in the figures. In Fig. 2 the signal strength is more or less uniform over the dorso-lateral region of the fish, whereas in Fig. 3 it increases as the fish comes to present its right or left side to the transducers. Variations in the form of the two polar diagrams could not be related to any difference in length or sex of the fish or to differences in the method of suspension. The difference between the polar diagrams might possibly be an effect of size. Cushing (1955) has shown with fish models that small changes in the dorso-ventral dimension can produce variations in polar diagrams. In one or two cases when the swimbladder was being punctured the fish was found to have a well-developed median ovary. After the check measurement with the false swimbladder, this ovary was removed and the measurement repeated. No measurable effect on the polar diagram of the fish was noted. The results have been summarized in Table 1 to show the reduction in echo signal amplitude following the emptying of the swimbladder when the dorsal surface of the fish is normal to the transducers and when it is 10° off to the left or right. The results show that the echo amplitude is reduced by 52% of its maximum value when the swimbladder of the fish is punctured. A change of pulse length from 0·5 to 1·0 msec. had no effect.

From the point of view of fish detection by the echo sounder the important feature of the results is the strength of the echo signal obtained from the dorsal aspect of the fish. In order to present the results in a more useful form from this point of view, each polar diagram carries three scales: (*a*) relative echo signal amplitude; (*b*) target strength in db. relative to a sphere of 2 m. radius (see Appendix); (*c*) scattering cross-section in $cm.^2$ (see Appendix).

Examination of the results shows that at 30 kc./s. the target strength of the dorsal aspect for the perch, and also, therefore, for fish of similar size and structure, is about -35 to -38 db., and that the scattering cross-section of this aspect is from 15 to 40 $cm.^2$. The variations obtained, as already stated, could not be explained by physical or biological differences in the fish, nor yet by any inconsistencies in the apparatus or in the method of measurement.

(ii) *Rotation about the vertical axis.* Typical polar diagrams are shown in Fig. 4 for measurements upon: (*a*) a fish with the swimbladder full; (*b*) a fish with the swimbladder empty; (*c*) a false swimbladder alone; (*d*) a fish with a false swimbladder.

The symmetry of cases (*a*), (*c*) and (*d*), with respect to the dorso-ventral axis is noticeable, and so is their similarity in shape. From Table 2 it will be seen that the angular widths to the 1st minimum of the large lobes in cases (*a*) and (*d*) are close to those of the false swimbladder alone, case (*c*). This is a further indication that the echo from the fish used in the experiment is primarily due to the swimbladder.

Again, removal of the swimbladder has considerable effect on the strength of the signal received from the fish. One experiment was carried out to examine the effect

TABLE 1. *Relative signal strengths received from perch during rotation about the longitudinal axis*

(Pulse length 0·5 msec. unless stated.)

Fish no.	Length (cm.)	Series	Relative signal strength: Swimbladder full, Left, 10°	Swimbladder full, Dorsal, 0°	Swimbladder full, Right, 10°	Swimbladder empty, Left, 10°	Swimbladder empty, Dorsal, 0°	Swimbladder empty, Right, 10°	Percentage reduction in amplitude
1	22·5	(i)	84	98 90	89	45	45 48	44	47·5
		(ii)	75	90 89	96	45	48 48	50	
2	24·0	(i)	104	114 105	103	48	52 51	62	42·8
		(ii)	105	95 99	99	69	72 54	63	
3	20·5	(i)	55	64 61	60	35	27 35	37	39·6
		(ii)	50	52 48	52	29	36 30	38	
4	19·0	(i)	73	70 70	68	31	38 31	30	56·2
		(ii)	70	69 79	79	30	31 31	31	
5	21·5	(i)	145	152 150	151	46	44 53	54	64·5
		(ii)	141	145 150	152	54	52 59	59	
6	18·0	(i)	118	118 109	109	74	74 70	70	39·8
		(ii)	120	120 120	120	72	72 65	65	
7	16·5	(i)	97	97 95	95	40	40 38	38	60·2
		(ii)	99	95 95	95	38	38 37	37	
8	19·5	(i)	118	118 114	114	40	40 49	49	61·6
		(ii)	110	110 108	108	42	42 42	42	
9	20·5	(i)	125	131 131	132	59	68 65	61	52·6
		(ii)	118	128 123	125	50	60 57	60	
Pulse length 1·0 msec.		(i)	138	151 150	152	65	70 65	75	52·7
		(ii)	142	144 138	142	62	65 70	75	
						Mean reduction in amplitude			51·8

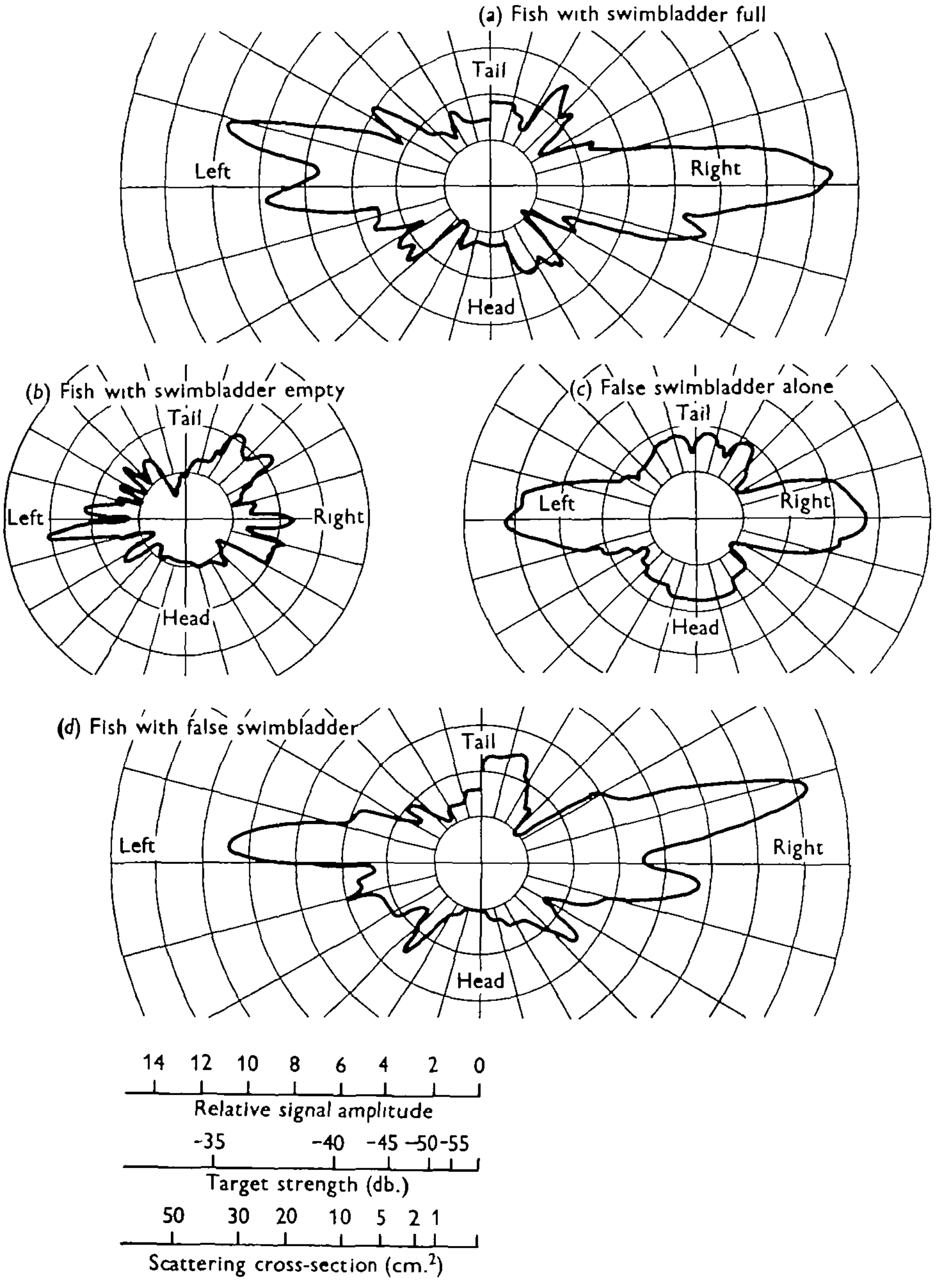

Fig. 4. Polar diagrams of relative signal amplitude, target strength and scattering cross-section obtained by rotating a fish about its vertical axis. Fish no. 3, 20·0 cm. long. False swimbladder 5 cm. long, 1·2 cm. diam., cylindrical, prepared with cork borer. Only one of the duplicate sets of results is figured in (*a*), (*b*) and (*d*). The polar co-ordinate scales have been put below the diagrams to avoid superimposition.

TABLE 2. *Comparison of polar diagrams obtained during rotation about the vertical axis*

	Fish 2. Length, 22 cm. False swimbladder: 5 cm. long, 1·2 cm. diam.		Fish 3. Length, 20 cm. False swimbladder: 5 cm. long, 1·2 cm. diam.	
	Angular width of main lobes to 1st minimum		Angular width of lobes to 1st minimum	
	Right	Left	Right	Left
Fish with natural swimbladder	54°	43°	71°	57°
Fish with false bladder	47°	52°	70°	66°
False swim-bladder alone	56°	56°	76°	67°

TABLE 3. *Relative peak signal strengths received from perch during rotation about the vertical axis*

(Pulse length 0·5 msec. unless stated.)

Fish no.	Length (cm.)	Series	Relative peak signal strengths: Swimbladder full, Left side	Swimbladder full, Right side	Swimbladder empty, Left side	Swimbladder empty, Right side	Percentage reduction in amplitude
1	19·0	(i)	92 109	101 133	50 50	45 45	67·6
		No tilt	92 109	133 124	47 42	40 40	
		(ii)	86 90	145 158	34 34	39 38	
		12° tilt	89 86	151 159	34 32	38 33	
		(iii)	132 121	130 130	39 38	36 35	
		40° tilt	110 120	142 137	38 36	35 35	
2	22·0	(i)	135 135	174 169	117 109	64 64	51·7
			132 132	169 169	92 88	59 59	
		(ii)	140 140	179 179	76 75	55 55	
			132 132	158 130	69 64	61 55	
3	20·0	(i)	109 109	140 140	58 58	45 43	62·7
			94 94	132 128	43 42	43 42	
		(ii)	108 108	140 140	49 49	42 42	
			111 111	120 110	40 40	35 35	
4	21·5	(i)	152 140	134 136	102 95	99 95	30·0
			137 127	99 74	85 73	81 75	
		(ii)	140 142	134 111	104 91	78 88	
			135 119	111 94	89 81	81 65	
5	20·5	(i)	120 118	132 132	56 53	60 58	53·3
			111 111	128 122	52 50	52 50	
		(ii)	112 113	135 125	62 60	59 59	
			111 101	118 118	58 51	55 55	
	Pulse length 1·0 msec.	(i)	150 144	161 158	70 65	74 68	53·9
			132 132	155 149	62 60	68 64	
		(ii)	147 141	161 154	75 70	70 70	
			135 125	150 151	67 59	70 70	
Mean reduction in amplitude							53·2

of tilting the fish at angles of 12° and 40° to the vertical axis during rotation, but this appeared to make but slight alteration in the strength or pattern of the signals returned. The peak signals returned by the fish when beam-on to the transducer seemed a reasonable measure of the contribution of the swimbladder to the echo and the four peak signals from the left and right sides during each experiment are summarized in Table 3. It will be seen that there is a reduction of 53% in the peak signal amplitudes following the emptying of the swimbladder.

The target strength of the lateral aspect of the normal fish is about −33 db. and that of the tail-on or head-on aspect is about −45 db. The corresponding values of the scattering cross-section are approximately 60 and 5 $cm.^2$. Removal of the swimbladder reduces the target strength of the lateral aspect of the fish by about 12 db. and the scattering cross-section by a factor of 12.

DISCUSSION

The main result of these experiments is to confirm (i) that the swimbladder plays a major part in determining the acoustic reflexion properties of the fish used, and (ii) that in general Cushing & Richardson (1955) correctly estimated that of the total echo energy from a fish, about 50% is returned from the swimbladder. Both conclusions (i) and (ii) are reached by considering the echo signal amplitudes received from the fish with and without its swimbladder. In addition, conclusion (i) is strengthened by a consideration of the polar diagrams obtained for the fish with its swimbladder and comparison of these diagrams with those obtained for a swimbladder alone.

It will be noted that the measurements were made by rotating the target relative to the combined projector-hydrophone system. Consequently, the results obtained are measurements of the amount of energy reflected in the direction of its initial incidence. This is not in accord with the usual methods of measuring scattered energy. The method used here is, however, relevant to the echo-sounding detection of fish, to the study of which the results and conclusions can be applied.

SUMMARY

1. Measurements were made under controlled conditions to determine the contribution of the swimbladder to the reflexion of acoustic energy from the perch, *Perca fluviatilis*.

2. The amplitude of the echo fell by 50% when the swimbladder was emptied; this was observed both when the dorsal surface and when the lateral surface faced the direction of the incident sound energy.

3. The polar diagram of the fish with its natural swimbladder is similar in shape to that obtained with a false 'Onazote' swimbladder.

Thanks are due to Messrs Kelvin and Hughes Ltd., Barkingside, Essex, and to Mr W. Halliday, Chief Physicist, Acoustics Division of Messrs Kelvin and Hughes Ltd., for permission to carry out the work, and also to Mr W. Thomas who helped considerably in preparing the apparatus and in making the measurements.

REFERENCES

CUSHING, D. H. (1955). Some echo sounding experiments on fish. *J. Cons. Int. Explor. Mer.* **20**, 266–75.

CUSHING, D. H. & RICHARDSON, I. D. (1955). Echo sounding experiments on fish. *Fish. Invest. Lond.* (Ser. 2), **28**, no. 4.

JONES, F. R. HARDEN (1951). The swimbladder and the vertical movement of teleostean fishes. I. Physical factors. *J. Exp. Biol.* **28**, 553–66.

PLATTNER, W. (1941). Études sur la fonction hydrostatiques de la vessie natatoire des poissons. *Rev. suisse Zool.* **48**, 201–338.

APPENDIX

(i) *Target strength*

For the reflexion of sound energy, it is known that

$$I_r = \frac{k}{r^2} I_0, \tag{1}$$

where I_0 is the intensity of the energy incident upon the target, I_r is the intensity of the reflected sound at a point, distance r from the target, and k is a factor whose magnitude is determined solely by the reflecting properties of the target.

The target strength T is defined as

$$T = 10 \log_{10} k, \tag{2}$$

substituting for k

$$= 10 \log_{10} \frac{I_r}{I_0} r^2. \tag{3}$$

In the experiments described the sound intensities I_r, I_0 were measured with linearly responding apparatus, so that if (for the given receiving transducer) V_0 and V_r are the received voltages corresponding to I_0 and I_r, respectively,

$$T = 10 \log_{10} \left(\frac{V_r}{V_0} r\right)^2. \tag{4}$$

Now r and I_0 (and so V_0) were constant throughout the experiments so that

$$T = 20 \log_{10} AV_r, \tag{5}$$

where $A = r/V_0$. The target strength is essentially a measure at a certain point of the level of the energy reflected from the target compared to that of the incident energy, the dispersion of energy due to the inverse square law being allowed for. The reference level is given by a target for which $k = 1$. It can be shown that a sphere of radius equal to 2 units of dimension in the dimensional system used is such a target. In these experiments the target strengths are referred to a sphere of radius 2 m. as reference target.

(ii) *Scattering cross-section*

The scattering cross-section σ_s is defined as that area perpendicular to an incident plane beam of sound energy such that the energy flowing through it is equal to the total energy scattered by the target in all directions. Thus, using the same notations as above,

$$4\pi r^2 I_r = \sigma_s I_0, \tag{6}$$

or

$$\sigma_s = \frac{4\pi r^2 V_r^2}{V_0^2} = BV_r^2, \tag{7}$$

where B is a constant, since r, V_0 were kept constant throughout the experiment.

Further discussion of these concepts is to be found in 'The physics of sound in the sea', *Summary Technical Report of Division* 6, *NDRC*, **8**, 1946 (Washington, D.C.), parts III and IV.