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The physical effects of an acoustic tag on the swimming performance of plaice and cod

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Drag measurements in a small flume show that the Mitson-West transponding acoustic tag developed at the Fisheries Laboratory, Lowestoft, has a frontal drag coefficient $C_{D0} = 0{\cdot}6$. For fish moving at constant speed the ratio of fish drag to tag drag is given by $D/d = 0{\cdot}82L^2C_D$, where C_D is an appropriate drag coefficient for the fish and L its length in cm. Acoustically tagged plaice, *Pleuronectes platessa* (36–52 cm length), and cod, *Gadus morhua* (50–70 cm length), tracked by sector-scanning sonar in the southern North Sea have been observed to swim at speed of 1 to 2 L s^{-1} through the water. Calculations with theoretical and experimental values of C_D show that the smallest of these fish could have been slowed down by 7% and the majority by rather less than 5%. The extra ower output required for a tagged fish to maintain the same steady speed as an untagged fish is between 3% and 5% and to maintain the same constant rate of acceleration less than 1%. The results suggest that the swimming performance of plaice and cod observed by sector-scanning sonar is unlikely to have been affected in any significant way by the addition of the acoustic tag.

Introduction

Acoustic tags are a valuable tool in the study of fish behaviour. The Mitson-West transponding acoustic tag (Mitson and Storeton-West, 1971) developed at the Fisheries Laboratory, Lowestoft has been used to determine the efficiency of the Granton otter trawl (Harden Jones et al., 1977) and to track plaice *Pleuronectes platessa*, (Greer Walker, Harden Jones and Arnold, 1978) and cod, *Gadus morhua*, in the open sea. The tag is tied externally to the fish, in plaice to the wire ring of a Petersen disc tag and in cod alongside the dorsal fin between two spaghetti tags. It is known that external tags can affect the swimming ability of small salmonids (Clancy, 1963; McCleave and Stred, 1975) and the objective of this work was to measure the drag force exerted by the Mitson-West tag and to estimate its effect on the swimming performance of plaice and cod.

Theory

A cylindrical body in axial flow experiences a drag force given by:

$$d = 0{\cdot}5\varrho_s \cdot C_{D0} \cdot A_f \cdot V^2 \qquad (1)$$

where C_{D0} is the frontal drag coefficient, A_f is the cross-sectional area of the cylinder, ϱ_s is the density of the fluid and V the velocity. The value of C_{D0} is determined, for a given fineness ratio (length/diameter), by the shape of the front end of the cylinder. For a blunt ended cylinder with a fineness ratio equal to 5, C_{D0} is approximately 0·8, while for a streamlined end C_{D0} is approximately 0·2 (Hoerner, 1965).

Material and methods

Acoustic tag

The Mitson-West transponding acoustic tag is contained in a polythene tube 5 cm long × 1 cm diameter filled with castor oil. The complete tag weighs 8·26 g in air and 4 g in sea water at 33 S $^0/_{00}$. The case is sealed by a small plug through which project two axial terminals and a transverse nylon cord, with which the tag is attached to the fish. The terminals are connected with fine wire just before a fish is released and the end of the plug filled with dental wax. The nylon cord is knotted across the end of the plug and covered with more dental wax. The result is a domed end virtually identical to the other end of the polythene tube, which is curved with a radius of 0·63 cm. The tag case used in these experiments was 5·12 cm long × 1·02 cm diameter.

Flume

The drag force exerted by the Mitson-West tag was measured in the flume described by Arnold (1969). The original recirculating pump has been replaced by a larger centrifugal pump with a capacity of 126 l s^{-1} at a total generated head of 9·1 m and new pipework of 20 cm internal diameter. A separate cooling system has been installed which recirculates sea water at 0·6 l s^{-1} from the sump over a stainless steel cascade cooler with a capacity of 33 kW. The new pump enables speeds of up to 1 m s^{-1} to be obtained at the full working depth of 30 cm with the flume in the horizontal mode.

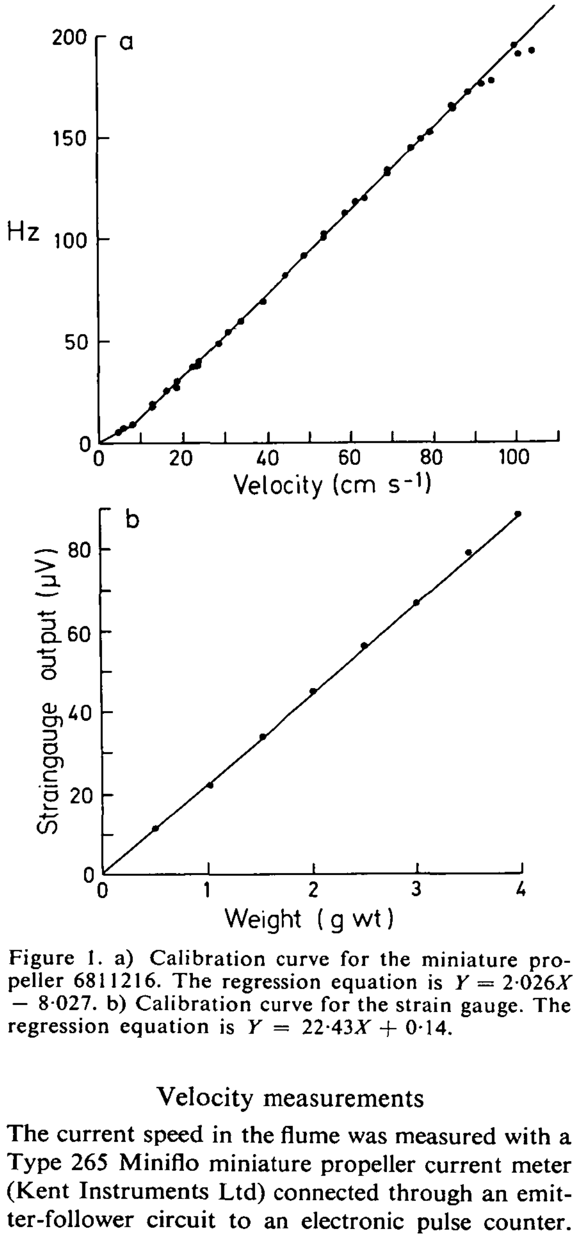

Figure 1. a) Calibration curve for the miniature propeller 6811216. The regression equation is $Y = 2{\cdot}026X - 8{\cdot}027$. b) Calibration curve for the strain gauge. The regression equation is $Y = 22{\cdot}43X + 0{\cdot}14$.

Velocity measurements

The current speed in the flume was measured with a Type 265 Miniflo miniature propeller current meter (Kent Instruments Ltd) connected through an emitter-follower circuit to an electronic pulse counter. The meter was fitted with a low-speed propeller (No. 6811216) and calibrated in No. 2 Towing Tank at the National Physical Laboratory at Teddington at speeds from 5 to 100 cm s^{-1} using an immersion depth of 40 cm and a separate carriage run for each speed. The time taken by the carriage to cover a measured 73·15 m was recorded automatically to 0·1 s. When necessary the canvas curtains in the tank were raised between runs to still the water. The results of calibrations on four separate dates are shown in Figure 1a. For the tag drag measurements the propeller was mounted in the Lowestoft flume one cm downstream from the trumpet exit, 10 cm from the far wall of the flume, and 16·7 cm above the bottom (Fig. 4).

The velocity profile in the boundary layer was measured with a pitot-static tube of standard NPL design, with an ellipsoid nose (Ower and Pankhurst, 1966) and an external diameter of 8 mm. The tube was connected to a paraffin-filled inclined tube manometer with a scale factor of × 20 (Airflow Developments Ltd), which was used in conjunction with the twin reservoir system described by Preston (1972). The manometer was read to the nearest 0·25 mm.

Flexure

The drag force measurements were made with a stainless steel flexure (61 cm long × 0·63 cm diameter) fitted with a pair of Micromeasurement EA/09/125BT strain gauges (Welwyn Strain Measurements Ltd) near one end. The gauges were cemented to the rod with BR 600 cement and were encased in Silastoseal-C (Midland Silicones Ltd). The rod was clamped vertically in an aluminium block attached to the moving table on a vertical screwstand (Fig. 2). It was mounted inside a 67 cm long steel tube of symmetrical aerofoil section (thickness: chord ratio = 0·34, chord 3·6 cm) which was rigidly clamped to the stand independently of the flexure. The leading edge at the bottom of the aerofoil tube was cut away to make an aperture (0·12 cm long × 0·6 cm wide) through which projected a 5·5 cm length of stainless steel threaded rod (0·24 cm diameter) which was attached to a swivel on the end of the flexure so that it could be rotated. The case of the acoustic tag was screwed to the rod with its curved end pointing upstream (Fig. 3a).

The strain gauges constituted two arms of an unbalanced Wheatstone bridge circuit supplied with 5 V DC from a stabilized voltage power supply across two corners. The output from the opposite corners of the bridge was monitored by a Beckman Type RM Dynograph recorder (Beckman-R11C Ltd), using a standard amplifier (type 482M8) and preamplifier (type 481B). The filter switch was set to give the frequency response of the amplifier an upper cut-off at approximately 0·3 Hz. The initial voltage produced by the strain-gauges with no load was offset by the zero control of the amplifier. The Dynograph pen was bypassed and the output signal of the amplifier taken to a Model 520.20 Servoscribe potentiometric chart recorder (Smith's Industries Ltd) set on the 100 mV scale with variable control. Full scale deflection was set with an input signal of 100 µV and the whole system calibrated in 10 µV steps using

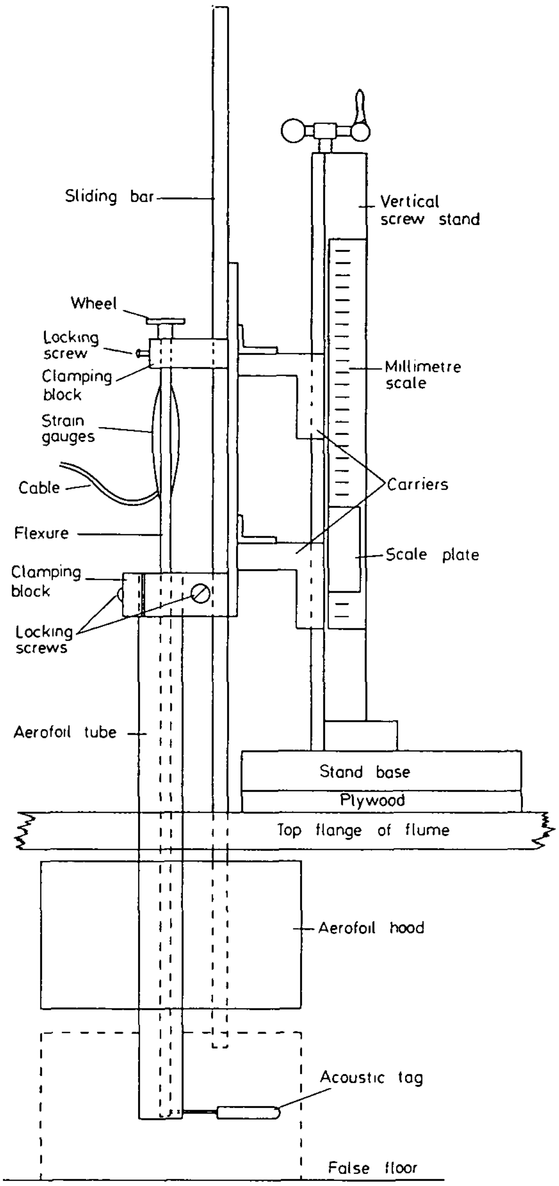

Figure 2. Screw stand assembly supporting the flexure and strain gauges.

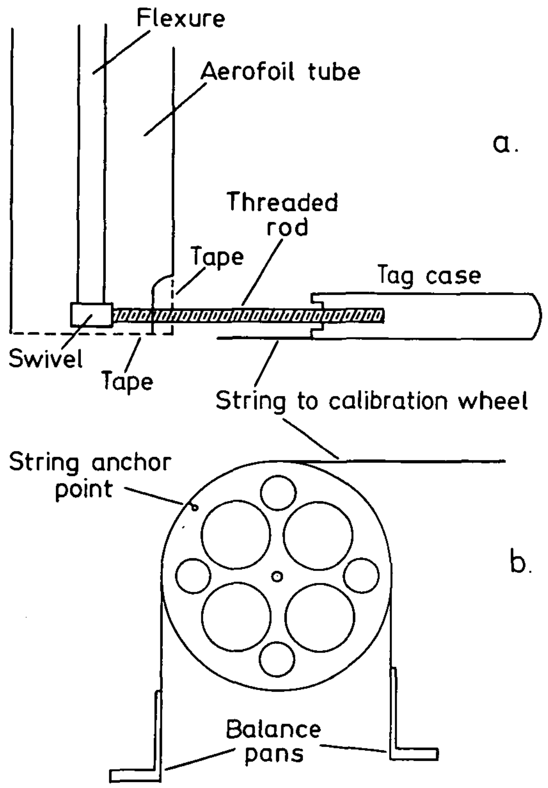

Figure 3. a) Detail of the attachment of the tag to the lower end of the flexure. b) Strain gauge calibration wheel.

a type 2003 DC calibrator (Time Electronics Ltd., 0·05% grade). The overall resolution of the system was 0·5 μV.

Calibration

The strain gauges and flexure were calibrated using a small perspex wheel (Fig. 3b) balanced on two supports. A horizontal thread of fine nylon connected a point on the circumference of the wheel to the lower rear end of the tag. Two balance pans of light aluminium alloy were attached to the wheel by a second thread running round the wheel and also attached to it; two grooves were machined round the circumference to guide the threads. The wheel was first zeroed with counterbalance weights in the right hand pan. A series of weights from 0·5 to 4 g in 0·5 g steps was then added to the left hand pan and the output voltage of the strain gauges recorded. The calibration curve is shown in Figure 1b.

Experimental procedure

The measurements were made in the upstream section of the flume, into which was fitted a false floor made from an aluminium plate 100 × 30 cm. The plate was 0·3 cm thick and its leading edge was bevelled off underneath at an angle of 23°. The plate was mounted on 8 pillars (1·3 cm diameter) so that its upper surface was 6·7 cm above the bottom of the flume (Fig. 4). The centres of the pillars were 3 cm from the sides of the plate and the holding screws were countersunk in its top. The leading edge of the plate was 50 cm downstream from the exit of the trumpet.

The screw stand was mounted across the top of the flume so that the flexure and the aerofoil tube projected down into the centre of the channel (Fig. 2). A streamlined hood of thin aluminium plate was fitted over the aerofoil tube and attached to a sliding vertical bar which passed through both clamping blocks. The hood was 12 cm high × 21 cm long so that it would stand on the false floor in the flume and cover the acoustic tag or alternatively be lifted clear of the water; its top was sealed with waterproof tape.

Before any measurements were made, or the strain gauges calibrated, the flexure rod was rotated in its supporting block using the wheel attached to its upper end until, for a constant force applied to its lower end, a maximum output voltage was obtained. The flexure was then clamped in place, the threaded rod on the lower end rotated to point upstream and the swivel locked in position. The aerofoil tube was lowered over the threaded rod and its leading edge and lower end sealed off with water proof tape, leaving only a small hole clear for the rod. It was necessary to enclose the flexure inside the aerofoil tube to prevent it vibrating at the higher current speeds. Without the acoustic tag there was no measureable drag on the threaded rod when the end of the aerofoil tube was taped off.

Measurements

The drag force on the tag was first measured in free stream with the tip of the tag 1·2 cm behind the leading edge of the false floor and its centre 10 cm above it (Fig. 4). Measurements were made at 15 speeds from 6 to 103 cm s^{-1}. The speed of water was increased firstly by increasing the volume of water flowing through the flume with the weir set at 15 cm height and subsequently by lowering the weir. The hood was lowered over the tag between each measurement so that the chart recorder zero could be checked and reset with the tag in still water without stopping the flume. At each of the 15 set speeds the hood was lifted clear of the water and the drag force recorded for about one minute. Zero drift usually occurred during this period and two separate measurements were therefore taken at the beginning and end of each chart trace, immediately adjacent to a still water zero reading. The measurements were converted from µV to g wt using the regression $Y = 22{\cdot}43X + 0{\cdot}14$ from Figure 1b. A predetermined correction was then applied to convert the reference speed measured at the trumpet exit to the local speed at the position of the tag, where the water accelerated a little over the plate.

Subsequently the drag was measured with the tag in proximity to the false floor. Vertical transects were made at three positions on the central axis of the flume with the tip of the tag 1·2, 50 and 80 cm behind the leading edge of the false floor (Fig. 4). The tag was positioned with its centre 0·51, 0·6, 0·7, 0·8, 1·0, 1·5, 2·0, 5 and 10 cm above the floor; scale zero was first set with the case of the tag just touching the false floor. The measurements were made at a nominal free-stream speed of 75 cm s^{-1} and two vertical transects were made at each of the three positions both raising and lowering the tag. The

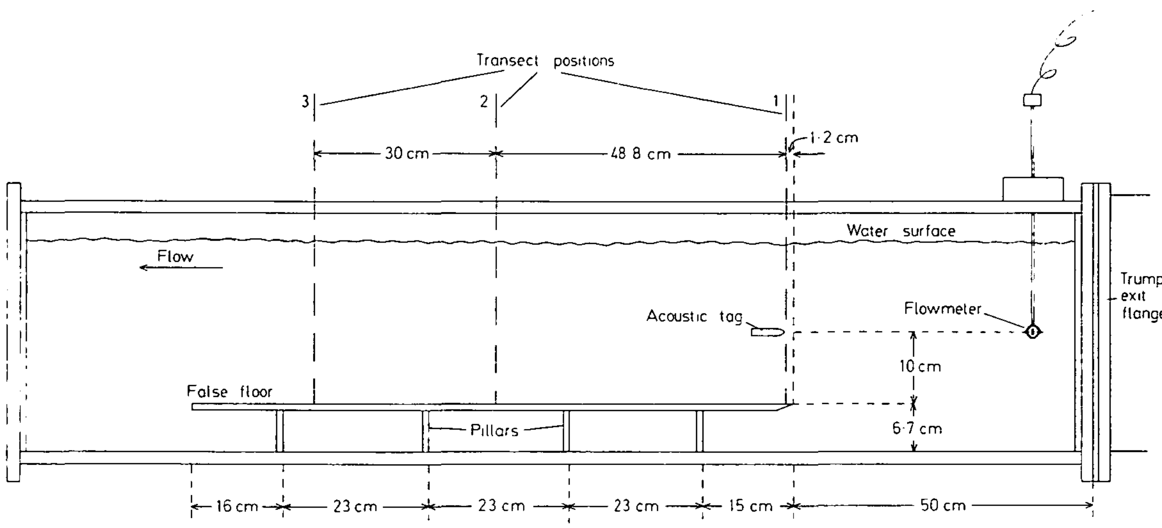

Figure 4. Tag transect positions in the upstream section of the flume. The flowmeter was offset by 5 cm from the centre line of the flume (see text).

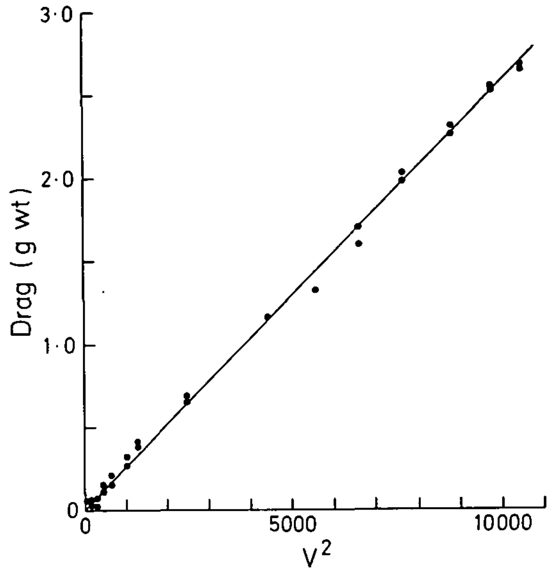

Figure 5. Drag of the acoustic tag (g wt) in free stream plotted against the square of the water speed measured in cm s^{-1}. The regression equation is $Y = 2{\cdot}57 \times 10^{-4}X$.

recording system was again zeroed with the hood over the tag before each reading.

The boundary layer velocity profile was then measured at the same three positions along the axis of the plate with the centre of the pitot-static tube set at heights of 0·6, 0·8, 1·0, 1·5, 2, 5 and 10 cm, again with a nominal free-stream speed of 75 cm s^{-1} measured at the trumpet exit.

Results

Drag in free stream

The results of the free-stream measurements are shown in Figure 5 with drag force in g wt plotted against the square of the corrected speed. The fitted regression line has the equation $Y = 2{\cdot}57 \times 10^{-4}$ X and the equivalent frontal drag coefficient calculated from Equation (1) with $\varrho_s = 1{\cdot}026$ and $A_f = 0{\cdot}817$ cm² is $C_{D0} = 0{\cdot}6$.

Drag in proximity to the plate

The boundary layer velocity measurements are shown in Figure 6a for the three positions along the axis of the plate. At $x = 1{\cdot}2$ cm the speed was effectively uniform from $h = 2$ cm down to $h = 0{\cdot}4$ cm but at $x = 50$ cm, where the boundary layer was already well developed, the velocity profile was described by the equation $\ln h = 0{\cdot}077\ V - 5{\cdot}7$ from $h = 0{\cdot}4$ cm to $h = 1{\cdot}3$ cm. At $x = 80$ cm the profile was similarly described by the equation $\ln h = 0{\cdot}076\ V - 5{\cdot}42$ for heights up to 1·5 cm. At all three points there was a slight decrease in free-stream speed from $h = 2$ to $h = 10$ cm. The equivalent mean reference speed is shown for each profile in Figure 6; in each case the standard error was 0·1 cm s^{-1}.

Table 1. Effect of proximity to a plane surface on the frontal drag coefficient of the acoustic tag

Height above plate y (cm)	Drag coefficient (C_{D_0}) $x = 1{\cdot}2$ cm	$x = 50$ cm	$x = 80$ cm
0·5	0·50	0·56	0·54
0·6	0·53	0·57	0·58
0·7	0·54	0·59	0·56
0·8	0·56	0·60	0·55
1·0	0·57	0·60	0·58
1·5	0·59	0·60	0·57
2·0	0·61	0·60	0·58
5·0	0·61	0·60	0·57
10·0	0·60	0·57	0·57

The profiles in Figure 6a were used to calculate the expected drag force at each point on the three tag transects. The local speed at each height was first calculated from the appropriate regression or from the mean of the actual free stream measurements. This value was then multiplied by the ratio of the appropriate reference speeds shown in Figure 6 (1·052 at $x = 1{\cdot}2$ cm; 1·061 at $x = 50$ cm; 1·084 at $x = 80$ cm) and substituted in Equation (1) taking $\varrho_s = 1{\cdot}026$, $A_f = 0{\cdot}817$ cm² and $C_{D0} = 0{\cdot}6$. There was no significant difference between the expected and measured values (Fig. 6b) either in the free-stream data ($h = 2$ to $h = 10$ cm for all three transects) or in the boundary layer at $x = 50$ cm and $x = 80$ cm. In no case did the difference between the two values exceed 0·1 g wt, an error which is consistent with the data in Figure 5. At $x = 1{\cdot}2$ cm, however, the measured values were clearly well below the expected values when the centre of the tag was 1 cm or less from the plate but the reason for this is not clear. The equivalent values of C_{D0} are given in Table 1, which shows a fall from 0·6 in free stream to 0·5 at $h = 0{\cdot}5$ cm. The combined free-stream data for all three transects gave a mean value of $C_{D0} = 0{\cdot}59$ with a standard error of 0·006 and 95% confidence limits of 0·58 and 0·6. It is clear, therefore, that attaching a tag close to a surface does not result in an increase in the value of C_{D0}, and in fact there may be a slight reduction. Taking the free-stream value of 0·6 may therefore result in a slight overestimate of the tag drag experienced by the fish.

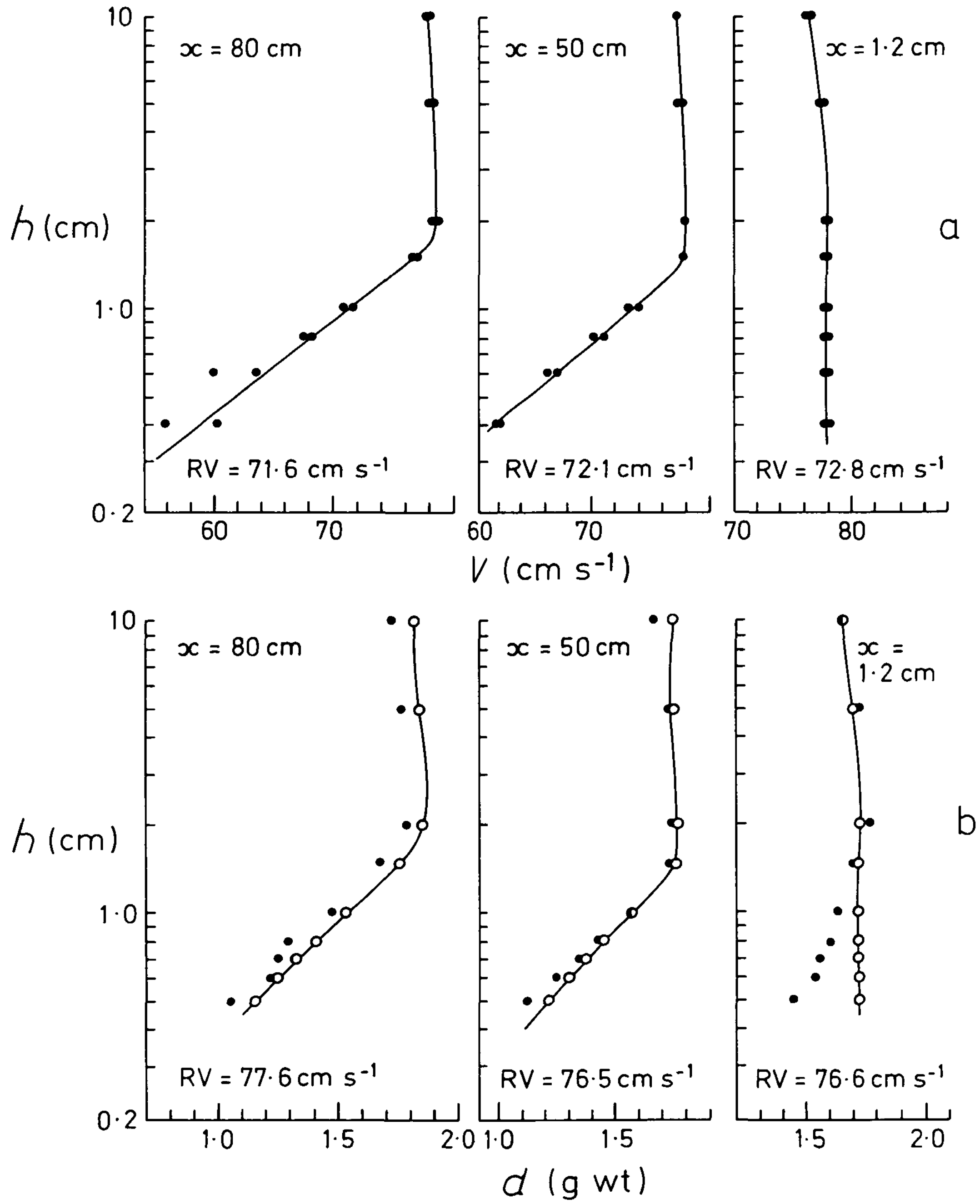

Figure 6. a) Boundary layer velocity profiles above the false floor. b) Measured (●) and expected (○) values of tag drag in proximity to the false floor. *RV* is the reference velocity measured in free stream by the miniature propeller (see Fig. 4 and text for further details). x = distance from leading edge of false floor.

Behaviour of the tag on the fish

If the tag were to oscillate while the fish was moving through the water its drag force would be increased, perhaps significantly. Observations were therefore made in the flume on the behaviour of the tag attached to a live plaice of length $L = 25$ cm. The Petersen tag was positioned 9 cm behind the nose of the fish and 3 cm to the left (dorsal fin) side of the centre line. The tag was attached to it by a 1 cm length of nylon cord so that its leading edge was 10 cm behind the nose of the fish.

At a free-stream water speed of 38·5 cm s^{-1} (1·5 L s^{-1}) the fish swam slowly upstream in midwater and the tag remained lying on its back the whole time. At a water speed of 78·5 cm s^{-1} (3·1 L s^{-1}) the fish swam in bursts of short duration (about 20–30 s) in midwater but made little progress upstream. The tag then streamed horizontally behind the point of attachment. There was a gap of 2 to 3 mm between the lower leading edge of the tag and the top of the fish but the rest of the tag was well clear of the fish, whose swimming movements were apparently unimpeded by the tag. The tag made no perceptible oscillations being apparently held steady by inertial forces. It is concluded that when the fish is gliding or swimming freely the drag force of the tag is not increased to any significant degree by oscillation.

When the fish was on the bottom the tag lay sloping diagonally down its ocular surface as in still water. The tag did not align itself to the flow although, at higher speeds, it did roll gently to and fro, apparently as a result of the interaction of the forces of gravity and current rather than of vortex shedding.

Ratio of tag drag to fish drag

Fish moving at constant speed

A fish moving at a constant speed experiences a frictional drag force given by $D = 0{\cdot}5\varrho_s A C_D V^2$, where A is its total wetted area and C_D is an appropriate drag coefficient. The same fish with an acoustic tag attached to it experiences an increased drag $D + d$, where d is the tag drag at speed V, and will be slowed down unless it increases its power output. The total drag $D + d$ experienced by the tagged fish is equivalent to that experienced by the untagged fish swimming at a slightly greater speed V', so that $D + d = 0{\cdot}5\varrho_s A C_D V'^2$. At speed V, however, the ratio of tag drag to fish drag is given by $d/D = A_f C_{D0}/A C_D$ and $D + d = D(1 + d/D)$. The speed V' is therefore given by $V'^2 = D(1 + d/D)/0{\cdot}5\varrho_s A C_D$ or $V'^2 = (1 + d/D)V^2$, and the decrease in speed produced by the tag by:

$$V/V' = 1/\sqrt{(1 + d/D)} \qquad (2)$$

The power output of the untagged fish is similarly given by $P = 0{\cdot}5\varrho_s A C_D V^3$, so that the extra power required by the tagged fish to swim at the same speed as the untagged fish is given by $P'/P = V'^3/V^3$. Substituting for $V' = \sqrt{(1 + d/D)}V$ from Equation (2) gives

$$P'/P = (1 + d/D)^{3/2} \qquad (3)$$

Given a reasonable estimate of tag drag the difficulty in evaluating the ratios V/V' and P'/P is in assigning an appropriate value to the drag coefficient C_D for the fish. The problem is greatest with fish that use both body and caudal fin for propulsion and which swim in the anguilliform or carangiform mode (Webb, 1975a). There is, however, no reason to doubt that when gliding these fish incur a similar drag to that of an equivalent rigid body (Bone, 1975), so that using a theoretical or experimentally determined value of C_D it is possible to make a reasonable estimate of V/V' for a gliding fish. It is also possible, although with less certainty, to estimate the values of V/V' and P'/P for an actively swimming fish, since it has been shown (Hertel, 1966; Lighthill, 1971; Webb, 1971; Webb, 1975a) that the drag incurred by the swimming fish is some 3 to 5 times that of the equivalent rigid body. These values apply to both plaice and cod, which swim in the anguilliform and sub-carangiform modes respectively (Webb, 1975a). As a result of the semi-ellipsoid shape of a plaice (Arnold and Weihs, 1978) there is a speed increment over the ocular surface which could increase V' by up to 10% (Weber, 1957), if the tag was attached at the point of maximum thickness. The corresponding power increase would theoretically be 30% but the effect is reduced by the boundary layer and the tag is attached well away from the point of maximum thickness. In practice, therefore, V' is increased by very much less than 10% and given the uncertainty in assigning a value of C_D to the fish no correction has been made in calculating V/V'.

It is difficult to measure the drag of a dead or anaesthetized fish because fluttering movements of the body and fins augment the drag and produce an artificially high value of C_D. Nevertheless, values close to theoretically expected ones have been determined experimentally in towing tanks using relatively rigid fish (Webb, 1975a). Sundnes (1963) achieved such results with a number of species by inserting stainless steel rods into the bodies of freshly-killed fish and filling the abdominal cavity with quick-setting cement. His data (Sundnes, 1963, Fig. 3) for a 54 cm long plaice, replotted with the square of the towing speed along the abscissa, give a linear relationship with $D = 0{\cdot}013 V^2$. The equivalent drag coefficient is therefore $C_D = 0{\cdot}013/0{\cdot}5\varrho_s A$. The total

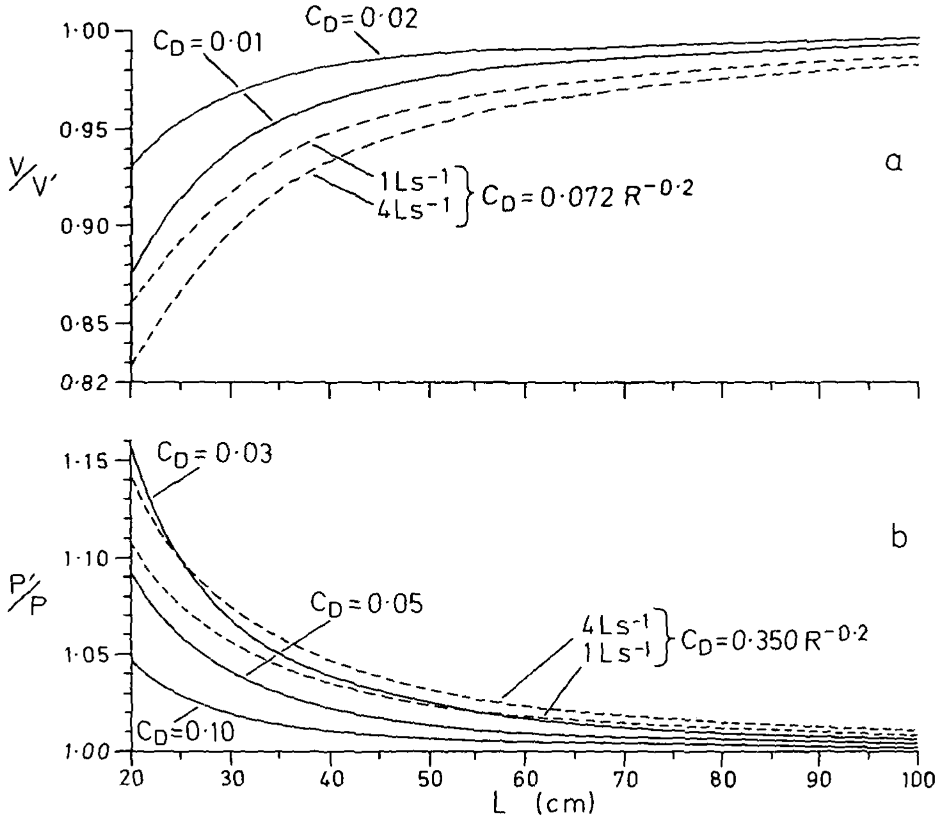

Figure 7. a) Reduction in speed of gliding fish caused by the acoustic tag. b) The extra power output required for a tagged fish to maintain the same swimming speed as an untagged fish of the same length. The solid lines represent constant values of C_D, the dashed lines values of C_D calculated from Reynolds number R.

area of a plaice of length L with its marginal fins fully extended is $A_t \simeq 0{\cdot}6L^2$, whilst the body area only is $A_b \simeq 0{\cdot}4L^2$ (Arnold and Weihs, 1978). The coefficient for a gliding plaice of 54 cm length therefore has a value between 0·01 and 0·02, depending on the extent to which the fins were extended in Sundnes' experiments. Sundnes also measured the drag of a cod (L = 113 cm) and his data give a value of $C_D \simeq 0{\cdot}01$, assuming a wetted area $A_t = 0{\cdot}4L^2$ (Webb, 1975a).

Taking $A_f = 0{\cdot}817\,\text{cm}^2$, $C_{D0} = 0{\cdot}6$ and $A = 0{\cdot}4L^2$, the ratio $D/d \approx 0{\cdot}816L^2\ C_D$ and this value has been used to calculate the ratios V/V' and P'/P for fish ranging in length from 20 to 100 cm. Figure 7a shows curves of V/V' for $C_D = 0{\cdot}01$ and 0·02, from which it can be seen that a fish of 40 cm length gliding through the water experiences a reduction in speed of between 2 and 4% as a result of the tag, whilst one of 70 cm has a reduction of only about 1%. Figure 7b similarly shows that to maintain the same swimming speed as an untagged individual a 40 cm tagged fish has to increase its power output by between 1% and 4%, while a 70 cm fish will only have to make an increase of 1·5%. An alternative approach is to calculate the fish drag theoretically taking $C_D = 0{\cdot}072R^{-0{\cdot}2}$ for a gliding fish and $C_D = 0{\cdot}35R^{-0{\cdot}2}$ for a swimming fish (Webb, 1975a, Equations 31, 76 and 78), where Reynolds number $R = LV/\nu$, and ν is the kinematic viscosity of water. In this case C_D is dependent on the speed as well as the length of the fish. Values of V/V' (Fig. 7a) and P'/P (Fig. 7b) have therefore been calculated for specific swimming speeds of 1 L s^{-1} and 4 L s^{-1}, a range which encompasses the cruising speeds reported for fish of over 30 cm in length swimming in the anguilliform and sub-carangiform modes (Webb, 1975a). The lower value of C_D derived in this way results in a slightly greater speed reduction for the gliding fish but does not significantly increase the power output of the swimming fish.

Fish accelerating

An accelerating fish has to work against both frictional drag and its own mass. Taking $D = KU^2$, the work done against drag by a fish accelerating at a constant rate a from rest ($U_0 = 0$) to a final speed U is given by

$$W_D = K_0 \int_0^x U^2\, dx \qquad (4)$$

where x, the distance covered during acceleration, is calculated by standard Newtonian mechanics from $U^2 = U_0^2 + 2ax$. The work done per unit distance crossed is therefore given by $W_D = K\, a\, x^2$ and the additional work-per-unit distance required to accelerate the tag by $W_d = k\, a\, x^2$, where $k = 0{\cdot}5\varrho_s A_f C_{D0}$. It follows that $W_d/W_D = k/K$ so that $W_d + W_D = W_D' = (1 + k/K)W_D$. Substituting for $k = d/U^2$ and $K = D/U^2$ the extra work required to accelerate the tag against frictional drag is given by

$$W_D'/W_D = (1 + d/D) \qquad (5)$$

If the fish has a mass M and it also moves an added mass of water equal to 0·2 M (Webb, 1975a), then the inertial component of the work done during acceleration is given by $W_M = 1{\cdot}2\, M\, 0{\cdot}5\, (U^2 - U_0^2)$. Similarly if the tag has a mass m, $W_m = 0{\cdot}5\, m\, U^2$. The total work against inertia $W_M' = W_m + W_M$ is therefore obtained from the ratio $W_m/W_M = 0{\cdot}5\ m\ U^2/0{\cdot}6\ M\ U^2$ and

$$W_M'/W_M = (1 + 0{\cdot}83\ m/M) \qquad (6)$$

The ratio of work done against drag to work done against inertia is given by

$$W_D/W_M = K\ a\ x^2/0{\cdot}6\ M\ U^2,$$

which, taking $U^2 = 2ax$, $A = 0{\cdot}4\ L^2$, $M = \varrho V$ and $V = \alpha L^3$, reduces to

$$W_D/W_M = 0{\cdot}166\ \varrho_s C_D x/\varrho\alpha L.$$

The density of most fish (Harden Jones and Marshall, 1953) is such that $\varrho_s/\varrho \simeq 1$ and $\alpha \simeq 0{\cdot}01$ (Webb, 1975a), so that $W_D/W_M \simeq C_D x/0{\cdot}06L$. The relative importance of work against drag therefore increases with the distance and thus the time over which the fish accelerates. Experimental results with rainbow trout (*Salmo gairdneri*) suggest that with a mean acceleration rate of 13 m s^{-2} (maximum rate 42 m s^{-2}) the work done against drag is about 18% of total overall work done during acceleration (Webb, 1975b).

Maximum acceleration rates of 40 to 50 m s^{-2} have been reported (Gero, 1952; Gray, 1953; Fierstine and Walters, 1968; Weihs, 1973a; Webb, 1975b) for perch, trout, pike and tuna with maximum speeds of up to 20 L s^{-1} achieved in periods of less than 0·1 s. Overall mean rates of acceleration are probably somewhat lower at 10 to 20 m s^{-2} with maximum speeds of 8 to 10 L s^{-1} (Weihs, 1973a; Webb, 1975b).

A fish of $L = 40$ cm and $C_D = 0{\cdot}03$ accelerating at a rate $a = 40$ m s^{-2} to a final speed $U = 10\ L\ s^{-1}$ has to do a total of $77{\cdot}2 \times 10^6$ ergs of work, of which 20% represents work against drag. The total work required to achieve the same rate of acceleration and final speed with the acoustic tag is $77{\cdot}9 \times 10^6$ ergs, an overall increase of only 0·9% comprising increases of 0·5% and 2·5% in work against inertia and frictional drag respectively. The ratio of the two components of work is not significantly altered by the addition of the tag. With lower final speeds or with higher values of C_D of 0·06 and 0·1 the total increase in work as a result of the acoustic tag is rather less than 1%.

Observations on acoustically tagged fish

Plaice (Greer Walker et al., 1978) and cod (Greer Walker and Arnold, unpublished observations) tracked in the southern North Sea have ranged in length from 36 to 52 cm (mean 41 cm) and 50 to 70 cm (mean 60 cm) respectively and have been observed to swim at speeds of 1 to 2 L s^{-1} through the water. When gliding the smallest of these fish has therefore probably been slowed down by not more than 7%, whilst for the majority the value is probably rather less than 5% (Fig. 7a). For a 40 cm fish the actual speed reduction at 1 and 2 L s^{-1} would be 2·8 and 5·6 cm s^{-1}. To maintain the same speed as the untagged fish the extra power output for the plaice would have to be less than 5% and for the somewhat larger cod around 3%.

Plaice and dabs have been observed by divers (Hemmings, 1969; 1973) to be herded by the bridles of a Danish seine net, swimming at right angles away from the obliquely advancing ropes for distances of up to 5 m before resettling on the bottom. By a series of such reactions fish in the path of the gear collect in the mouth of the net, where they swim until, presumably fatigued, they fall back over the groundrope into the net itself. Acoustically tagged plaice (length range 30 to 50 cm) have similarly been observed (Harden Jones et al., 1977) to react to the boards of a Granton otter trawl by swimming at right angles to the axis of the gear into the path of the net at speeds up to 3 L s^{-1}. The behaviour of these fish has not yet been fully described, but the reaction appears to be essentially the same as that to the seine net. In one case, a 40 cm fish swam 1 to 2 m ahead of the door-to-door tickler chain at a speed of approximately 1·9 m s^{-1} (4·8 $L\ s^{-1}$) for one minute, covering 116 m through the water, before falling back into the net. It seems clear from the previous section that the acoustic tag will not have significantly reduced the rate of acceleration of fish which reacted to the doors of the gear. Similarly, it seems unlikely that the tag will have seriously impaired the endurance of fish swimming in front of the net. For a 40 cm fish swimming at 4·8 $L\ s^{-1}$ with $C_D = 0{\cdot}35R^{-0{\cdot}2}$, the ratio $V'/V = 1{\cdot}016$ so that the fish is equivalent to an untagged fish swimming at 1·95 m s^{-1}. Endurance curves are not available for the plaice but data exist for the winter flounder *Pseudopleuronectes americanus* (Beamish, 1966) for fish of 19 to 23 cm in length, swimming at speeds up to 6·6 $L\ s^{-1}$, at temperatures between 5° and 11 °C. These data suggest that at 4·8 $L\ s^{-1}$ a speed increase of 1·6% would result in a reduction of 3 to 6% in endurance time. Without the acoustic tag the 40 cm plaice observed swimming ahead of the Granton trawl for 116 m might therefore have been expected to have swum for a further 2 to 4 s or 4 to 7 m, assuming that it was swimming at its maximum prolonged speed (Webb, 1975a).

These results suggest that in the short term the swimming behaviour of plaice and cod observed by sector-scanning sonar is unlikely to have been significantly affected by the acoustic tag. Evidence from returns of acoustically tagged fish from the commercial fishery suggest similarly that the tag has little effect on the fish in the long term. A total of 97 plaice and 13 cod have been abandoned with acoustic tags still attached to them and three cod have been recaptured in good condition, but without the acoustic tag, after periods of 13, 38 and 230 days at liberty. Of the plaice, 22 have been returned without the acoustic tag after periods of 4 to 1087 days at liberty and a further 22 with the acoustic tag still attached after periods of 3 to 726 days. Most of these fish have been in good condition and none has had injuries attributable to the acoustic tag. The distribution of recaptures of the plaice with the acoustic tag still attached is generally similar to that of returns from recent conventional plaice tagging experiments in the southern North Sea and the overall recapture rate of 45% is also approximately the same (R. C. A. Bannister, personal communication).

Buoyancy of fish

Induced negative buoyancy is known to affect fish behaviour. Negatively buoyant fish such as mackerel and tuna, which swim continously to avoid sinking, compensate for the extra weight of a tag by swimming faster. Fish with swimbladders, given sufficient time, counteract the increased weight by secreting oxygen into the swimbladder (Gallepp and Magnuson, 1972) or by gulping air (Fried, McCleave and Stred, 1976).

Negatively buoyant fish

Plaice have no swimbladder and are negatively buoyant. Fish of 36 and 52 cm length have weights in air of approximately 440 g and 1330 g respectively, which assuming a mean density of 1·076 (Arnold and Weihs, 1978), are equivalent to submerged weights of 20·3 and 61·8 g respectively. The addition of the Mitson-West tag with a submerged weight of 4 g increases these submerged weights by 20% and 6% respectively and to stay up in midwater an acoustically tagged plaice must produce an equivalent increase in lift either by swimming faster or by increasing its angle of attack to the water. The equivalent increases in density are 0·9% and 0·3% to values of 1·086 and 1·079, which are within the range of densities of 1·065 to 1·088 found by Lowndes (1955) for freshly-caught plaice.

Arnold and Weihs (1978) have shown that, unless it counteracts the lift and drag forces produced on it by the current, a plaice resting on a flat bottom and heading upstream is displaced downstream when the current speed reaches U_s and is lifted off the bottom when it reaches a higher speed U_L. The slip speed U_s, measured at 10 cm above the bottom, is given by $U_s^2 = W_0/\varrho_s A_f$, where W_0 is the submerged weight of the fish in still water and A_f is its projected frontal area. For plaice of 36 to 52 cm length the values of U_s are increased by 3 to 9% by the addition of the tag and the fish should therefore be able to hold station on the bottom in a current of a given speed for a proportionately lower expenditure of energy. The increased density will also result in a corresponding reduction of work against the lift force exerted by the current. The addition of the tag will thus be of help to a plaice opposing a current on the sea bed. A tag could also save energy in midwater if the fish were able to use the swimming and gliding mode of progress suggested by Weihs (1973b).

Neutrally buoyant fish

Initial tracking experiments with acoustically tagged cod (Greer Walker and Arnold, unpublished results) have shown that it is necessary to release the fish in cages and hold them at depth until they have achieved neutral buoyancy. Otherwise the fish remain at the surface for long periods, which makes tracking unrealistic.

A neutrally buoyant fish in hydrostatic equilibrium at the sea surface has a submerged weight $W_0 = 0$

and a swimbladder volume approximately 5% of its overall volume (Harden Jones and Marshall, 1953). When it is lowered in a cage the fish experiences an increased hydrostatic pressure and initially its swimbladder is compressed and its density increased in proportion to the depth to which the cage is lowered. Subsequently after secreting gas into the swimbladder over a period of hours the fish makes good the gas deficiency and returns to neutral buoyancy, when its density again equals that of the water. In sea water of density 1·026 an "idealized" cod of 1 kg weight ($\simeq$ 46 cm length) has a total volume of 975 ml comprising 50 ml of swimbladder and 925 ml of tissue (Harden Jones and Scholes, unpublished data). Lowered to a depth of 60 m the fish experiences a sevenfold increase in pressure and with a swimbladder gas deficiency of 300 ml at normal pressure has a density of 1·073. With an initial swimbladder volume V_s at the surface the gas deficiency (ml) at normal pressure for any depth is given by $G = V_s (p - 1)$ where p is the pressure in atmospheres at that depth. If r is the rate of secretion of gas into the swimbladder, the time taken to return to neutral buoyancy is given by $t = V_s(p - 1)/r$. When a negatively buoyant tag is attached to it the fish must increase its swimbladder volume to V_s' to regain neutral buoyancy. The time taken by the acoustically tagged fish to regain neutral buoyancy when lowered to depth is therefore given by $t' = V_s'(p - 1)/r$, so that the increase in adaptation time is given by $t'/t = V_s'/V_s$. If the Mitson-West tag, with a submerged weight of 4 g, is attached to the "idealized" cod of 1 kg weight the ratio $t'/t = 50/50{\cdot}2 = 1{\cdot}004$. At 10°C the rate of gas secretion into the cod swimbladder is 0·077 ml kg^{-1} min^{-1} (Harden Jones and Scholes, unpublished data), so that lowered to a depth of 50 m this fish would require 54·1 h to equilibrate on its own and 54·3 h with the acoustic tag attached. Cod tracked in the southern North Sea have ranged from 50 to 70 cm in length so that the increase in adaptation time for these fish would be proportionately less.

Discussion

No attempt was made to measure directly the effect on swimming performance resulting from the addition of the Mitson-West acoustic tag of either plaice, which cannot be made to swim consistently in a conventional flume, or cod. An independent check on the calculations is thus not possible for these species but a tentative comparison can be made with McCleave and Stred's (1975) results for Atlantic Salmon (*Salmo salar*). They found that a dummy radio tag (3·1 cm long $\times$ 1·8 cm diameter) weighing 6·7 g in air and 1·25 g in fresh water reduced the critical swimming speed (Brett, 1964; Webb, 1975a) of large (22–26 cm length) smolts by 20% from 56·5 cm s^{-1} to 44·8 cm s^{-1}. Webb (1975a, Fig. 52) gives a measured drag coefficient $C_D = 0{\cdot}02$ for a swimming rainbow trout (*S. gairdneri*) of 28 cm length. Assuming this value for McCleave and Stred's smolts and taking $C_{D0} = 0{\cdot}8$ to allow for the proportions of their tag (fineness ratio = 1·7) one obtains a ratio $V/V' = 0{\cdot}83$, whilst backcalculating from the observed ratio $V/V' = 0{\cdot}8$ gives $C_{D0} = 1{\cdot}0$ for $A_f = 2{\cdot}54$ cm^2. Considering the uncertainty in the values of C_D and C_{D0} this represents a good agreement between theoretical and experimental results.

The drag measurements show that the Mitson-West acoustic tag has a drag coefficient $C_{D0} = 0{\cdot}6$, which reflects its relatively blunt leading edge. This coefficient could be reduced by a factor of 2 or 3 to a minimum value of 0·2 if the case were modified to have a fully streamlined upstream end (Hoerner, 1965). It is doubtful if the minimum value could be achieved in practice because of the mode of attachment to the fish and, in view of the apparently small value of d/D for both swimming and gliding fish, there seems little point in modifying the standard tag. A telemetry tag incorporating various sensors including a miniature compass could be rather larger than the existing tag and streamlining might then be necessary to obtain acceptable values of d/D.

Conclusions

1) In free stream the Mitson-West acoustic tag has a drag coefficient $C_{D0} = 0{\cdot}6$. In close proximity to a plane surface with a developed boundary layer the coefficient falls to $C_{D0} \simeq 0{\cdot}55$.
2) When attached to a plaice swimming at low speed (1·5 L s^{-1}) the tag remains lying on the back of the fish but at a higher speed (3 L s^{-1}) it streams horizontally behind the point of attachment. There is no significant oscillation of the tag.
3) For fish moving at constant speed and with $C_{D0} = 0{\cdot}6$ the ratio of fish drag to tag drag is given by $D/d = 0{\cdot}82\ L^2\ C_D$. Calculations with both theoretical and experimental values of C_D show that a gliding fish of 40 cm length is slowed down by the tag by probably not more than 5 to 7%. A swimming fish of the same length has to increase its power output by a maximum of 5% to maintain the same speed as an untagged fish.
4) A tagged fish accelerating at a constant rate has to increase its power output by less than 1% to maintain the same rate of acceleration as an untagged fish.

5) The results suggest that the swimming performance, and therefore by inference the swimming behaviour of plaice (36 to 52 cm length) and cod (50 to 70 cm length), is unlikely to be significantly affected by the acoustic tag.
6) The density of these fish is increased by less than 1% by the addition of the tag and the time required by the cod to return to neutral buoyancy, when lowered to depth in a release cage, is increased by less than 0·5%.

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