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A FLUME FOR BEHAVIOUR STUDIES OF MARINE FISH

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INTRODUCTION

The migration circuits of marine fish are related to ocean currents (e.g. Harden Jones, 1965) and it is thought that water movements may provide directional information for migrants on passage. Little is known of how marine fish respond to water currents, and studies of behaviour under controlled laboratory conditions are an essential parallel to observations at sea. A flume has been built for this purpose at the Fisheries Laboratory, Lowestoft.

Binnie, Davies & Orkney (1955) described an apparatus to produce a uniform current in a flume. It consists of a trumpet-shaped rectangular orifice inserted in the side of a large reservoir and discharging directly into an open channel of the same cross-section. Water flows through the flume by gravity only and falls freely into a sump, from where it is pumped back into the reservoir. Apart from the formation of boundary layers on the surfaces, the stream is uniform in depth and velocity and, provided care is taken with the stilling arrangements in the reservoir, the stream is free from turbulence. With a Froude number* greater than unity the only disturbance at the water surface is a slight draw-down at the exit of the channel. At a Froude number less than unity a weir is theoretically necessary at the exit to maintain the water level.

DESCRIPTION OF FLUME

1. *Circulation system*

The flume (Fig. 1*a*) was built in a controlled-temperature room (12·8 × 3·7 m.) which contained a long tank (9·5 × 1·4 × 1·1 m. deep) fitted with a re-circulating system (Fig. 1*b*). The pump (5 h.p., centrifugal, 1593 l./min.) delivered sea water through a single pipe (10 cm. bore) to a stop valve at each end of the tank. One valve was connected by a flexible hose to the stilling tank of the flume and the other ran to waste back into the tank, which acted as a sump. By adjusting the valves all the water could be directed into the stilling tank, or all to waste, or divided in any proportion between the two.

2. *Construction*

Because of shortage of space, the flume was built over the sump tank, with the stilling tank standing inside it (Fig. 1*b*).

Stilling tank. The reservoir (183 × 100 × 203 cm. deep) was made of a heavy wooden frame lined with 1·2 cm. resin-bonded marine plywood coated with Araldite resin paint. An inverted T-shaped pipe of rigid plastic, with its lower end perforated by

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* $F = V/(gd)^{\frac{1}{2}}$ where F is the Froude number, V is the uniform velocity of the stream, d is its uniform depth and g is the acceleration due to gravity (Binnie *et al.* 1955).

holes (2·5 cm. diameter) to break the force of the jet, delivered water to the bottom of the tank. It was positioned at the back to use the maximum volume for stilling the turbulence produced by the inflow. This was done by five vertical screens each with holes of a different size, the size decreasing towards the front of the tank. The first screen was a sheet of 1·2 cm. plywood with 2·5 cm. diameter holes at 5 cm. centres. The second was polythene mesh with 0·6 cm. square holes and the remaining three sheets were of Nylon mesh stretched tightly across the tank, with mesh apertures of

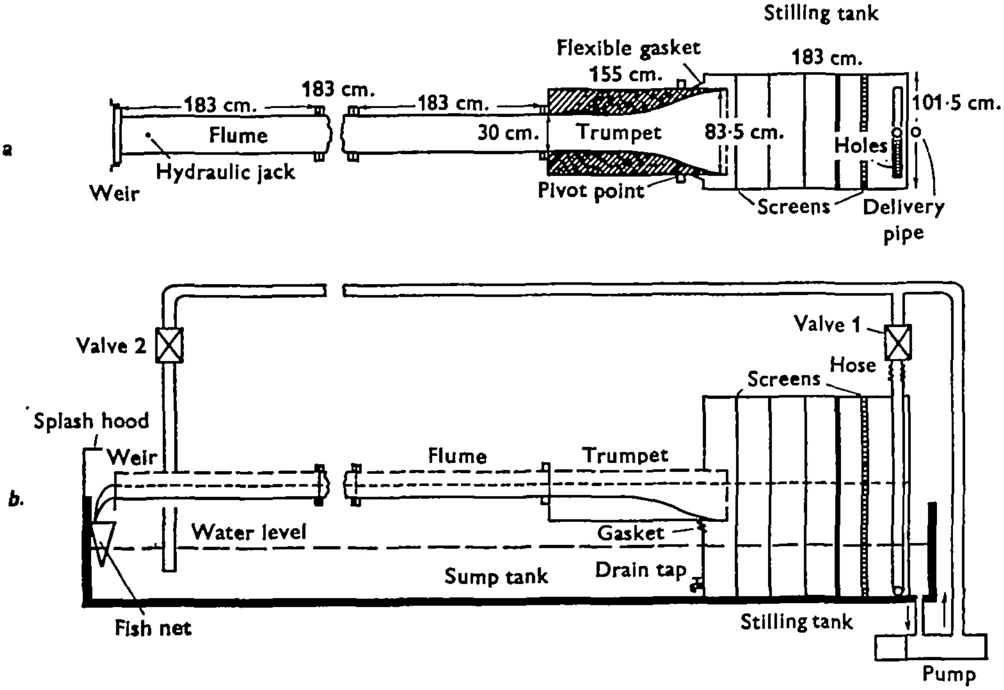

Fig. 1. (*a*) Plan and (*b*) elevation of flume.

Table 1. *Co-ordinates of the contraction*

(x = Distance from throat; y = half width; z = depth below level of flume floor.)

x (cm.)	y (cm.)	z (cm.)
0	15·0	0
11·7	15·0	0
23·4	15·1	0
35·1	15·3	0·04
46·8	15·4	0·1
58·5	15·8	0·3
70·2	16·4	0·9
81·9	17·4	1·9
94·2	19·4	3·7
105·4	22·6	7·1
117·1	27·4	13·1
128·8	32·9	20·6
140·5	37·5	26·5
147·5	39·1	28·3
152·4	39·9	29·0
154·9	39·9	29·0

1550, 560 and 410 μ. A sixth screen of 410 μ aperture Nylon mesh covered the end of the trumpet that projected into the stilling tank.

Contraction. The trumpet was made of thin plywood (0·4 cm.) screwed to vertical and horizontal formers inside an open-topped rectangular box. It was also coated with Araldite paint and repeatedly rubbed down with fine sandpaper to produce a smooth surface. Its co-ordinates are given in Table 1.

Flume sections. The channel was made from three Perspex sections, 183 × 30 × 32·5 cm. deep inside. The sides (0·6 cm. thick) were cemented into grooves in the base (1·2 cm. thick) to allow a clear line of sight across it just above the bottom. A projection of the base (4·7 cm. wide) on each side allowed the supporting frame to be clear of the channel, giving unobstructed observation through the bottom. The sections were flanged at each end and bolted together. Soft rubber gaskets were used to make a watertight seal, and the joint was smoothed inside with a plastic filling compound.

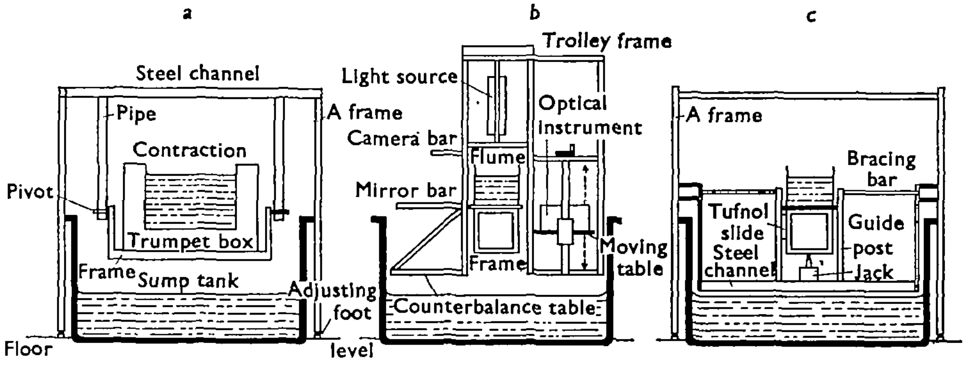

Fig. 2. Cross-sections of flume: (*a*) through contraction; (*b*) through instrument carriage; (*c*) through jack.

Weir. An adjustable weir plate, which could close the exit of the flume at any height from 0 to 18 cm., was attached to the last section. Vertical movement was produced by two levers attached to the base of the plate at one end and a nut on a horizontal rod at the other. The rod had two threads cut in opposite directions running out from the centre, so that as it was rotated the nuts travelled in opposite directions. Anticlockwise rotation caused the nuts to travel inwards and drive the plate upwards; clockwise rotation lowered the plate.

Supporting frame. The three flume sections and the contraction were supported by a single steel frame pivoted close to the stilling tank so that the flume could be tilted to accelerate the flow of water. The frame was supported by two pairs of steel A-frames standing outside the sump tank, each with levelling adjustments (Fig. 2*a*). The flume was held in the horizontal position by a fully-extended hydraulic jack (Fig. 2*c*). By lowering the jack a maximum gradient of 1 in 40 could be produced.

Instrument carriage. A 61 cm. gauge railway ran the whole length of the ceiling and the flume was positioned centrally beneath it. A steel frame (96·5 × 66 cm.) ran along the track on four runners, each with four nylon-tyred wheels, and from this was suspended a steel instrument carriage (Fig. 2*b*), bearing a table on each side of the flume. One table was provided with 45 cm. vertical movement, the other acted as a counterbalance. The carriage was fitted with a Bolex H16 cine-camera and four mirrors arranged to give simultaneous vertical and horizontal views of the flume on one frame of film (Nieuwenhuizen, 1964).

3. *Performance*

Fine control of water velocity and depth could be achieved by adjustment to the valves and weir. Table 2 summarizes data on velocity and depth in relation to valve settings and height of the weir. The maximum velocities obtainable at several depths with the flume in the level position are shown in Table 3*a*. By tilting the flume these could be increased (Table 3*b*).

Table 2. *Control of water velocity and depth with flume in level position*

Weir height (cm.)	Valve settings 0 = shut, 11 = open		Water depth (cm.)	Water velocity at half-depth (cm./sec.)
	Valve 1	Valve 2		
10	0·5	11	11·6	3·3
	0·75	11	12·2	5·5
	1	11	12·6	7·4
	1·5	11	12·9	8·5
	2	11	13·6	11·7
	3	11	14·6	14·5
	4	11	15·0	16·2
	5	11	15·2	16·8
	6	11	15·3	17·0
	7	11	15·4	17·4
	8	11	15·4	17·4
	11	11	15·4	17·4
	11	7	15·4	17·4
	11	6	15·5	18·0
	11	5	15·7	18·6
	11	4	16·1	20·3
	11	3	16·9	22·6
	11	2	18·0	26·7
	11	1	19·3	31·4
	11	0	20·5	34·6
9	11	0	19·5	36·9
8	11	0	18·4	40·4
7	11	0	17·2	42·8
6	11	0	16·1	45·2
5	11	0	15·0	49·8
4	11	0	13·8	55·0
3	11	0	12·6	59·7
2	11	0	11·4	64·3
1	11	0	10·9	69·1
0	11	0	10·8	69·1

Traverses of the flume showed that the velocity of the main stream was uniform in cross-section to the sensitivity of the optical technique used (see p. 678). With a stream 20 cm. deep moving at 30 cm./sec. the boundary layer on the centre-line of the bottom was approximately 1 cm. thick at 50 cm. from the downstream end of the contraction. This increased to approximately 6 cm. at 250 cm. and 9 cm. at 425 cm. downstream from the same point. The uniformity of the main stream and lack of turbulence was convincingly demonstrated by dropping crystals of potassium permanganate into the water.

Only at shallow depths and higher velocity was the surface of the water disturbed by a wave train, but the amplitude was so small (2–3 mm.) that it did not preclude observation from above. With deeper water or at slower velocities, the surface was smooth apart from small diagonal ripples originating from the sides of the trumpet and others formed at the joints of the flume sections. These ripples were barely perceptible at depths above 20 cm. At depths between 15 and 25 cm. with a gradient of 1 in 100 or steeper, a wave was formed at various points along the length of the flume.

The flume room was temperature-controlled but continuous pumping raised the temperature of the re-circulating water from 10° C. to approximately 13° C. after 8 hr. and 16° C. after 24 hr.

Table 3.

(*a*) (Maximum current velocities measured at half-depth at 50 cm. downstream from throat of trumpet.)

Water depth (cm.)	Height of weir plate (cm.)	Water velocity (cm./sec.)	Froude number	Water surface
10·8	0	69·1	0·67	Diagonal ripples from trumpet
10·0	0	64·3	0·65	Diagonal ripples from trumpet
15·0	5·0	48·6	0·40	Slight ripples
20·0	9·5	35·8	0·26	Smooth except for ripples from joints
25·0	14·2	29·0	0·19	Smooth except for ripples from joints
29·1	18·0 (max.)	24·4	0·14	Smooth

(*b*) (Increase in maximum current velocity produced by tilting flume.)

Flume gradient	Water depth (cm.)	Water velocity (cm./sec.)	Froude number	Water surface
Level	10·8	69·1	0·67	Diagonal ripples from trumpet
1 in 400	9·2 (mean)	82·0	0·86	Wave train—amplitude approximately 0·6 cm.
1 in 200	7·5	106·6	1·24	Very slight wave train—amplitude 1–2 mm.
1 in 100	6·4	113·8	1·43	Very slight wave train—amplitude 1–2 mm.
1 in 40	5·5	132·5	1·80	Very slight wave train—amplitude 1–2 mm.

MEASUREMENT OF WATER VELOCITY

A simple accurate method was required for measuring water velocity at any point in the flume. An optical technique (Seddon & Anwar, 1963) was chosen, which avoided the problems of using mechanical probes.

1. *Theory of optical technique*

Fine particles, which occur naturally in water, are made visible by scattering in a vertical beam of bright light. They are observed horizontally through a low magnification telescope and a cube or hexagon of optical glass. This is rotated at controlled speeds about a vertical axis, and the direction of rotation is such that the refracted line of sight travels in the same direction as the water. The apparent motion of the particles depends on the relative speeds of the water and cube. Three situations occur: (*a*) when cube speed is lower than particle speed, the particles are seen to travel horizontally across the field of view, but more slowly than at their true speed; (*b*) when cube speed is higher than particle speed, the particles are seen to travel in the opposite direction to their true horizontal direction and (*c*) at an intermediate cube speed, brightly illuminated particles suddenly appear, remain stationary in the horizontal direction and then abruptly disappear again. In the third situation, when the speed control is in the null position, the horizontal displacement y of a particle is related to the horizontal displacement x of the centre of the cube face by the expression:

$$\frac{y}{x} = 2\left(1 - \frac{\cos\theta}{\sqrt{n^2-\sin^2\theta}}\right), \tag{1}$$

where n is the refractive index of the glass and θ the angle between the optical axis and the cube face.

2. *Design of instrument*

A fixed focus lamp, consisting of a 1000 W, 240 V tungsten-iodine bulb (Atlas THB/1000/240) mounted 23 cm. behind a cylindrical lens (5 × 4 × 24·5 cm. focal length) was used to produce a light beam approximately 3 mm. thick at its focus. It was mounted vertically on the instrument carriage above the centre of the flume and could be rotated on a horizontal arm and turned in its mounting. The long axis of the beam could thus be placed parallel to the wall at any point across the flume. Vertical movement of the lamp was provided for focusing the beam and it was cooled by an electric fan.

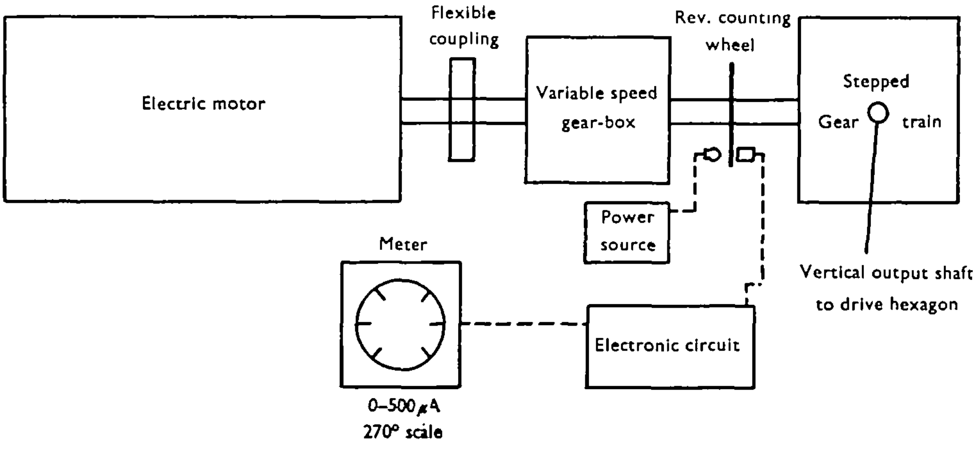

Fig. 3. Block diagram of mechanism used to drive hexagon.

Particles were observed through a small astronomical telescope of approximately × 2 magnification, fitted with cross wires and a graticule (scale divisions 1/100 in.). The optical glass section used was a hexagon 5·1 cm. high with 2·54 cm. sides and 3–4 min. of arc tolerance on each angle. Control of its rotational speed was achieved mechanically (Fig. 3) using a synchronous electric motor (1/80 h.p. Admiralty pattern, A 3989) and a variable speed gearbox (Kopp Variator type A 12 FX), which converted the 1500 rev./min. motor speed to any speed over the range 500–4500 rev./min. Before being stepped up or down through a gear train (S. G. Brown Limited, Seven-speed Turret gearbox Mk 1), the output shaft speed of the variator was measured electronically. Seven equally spaced holes (1 mm. diameter) were drilled on a circle (8 cm. diameter) through a small disk mounted on the shaft. A light bulb (6·5 V, 1 W) and a phototransistor (Mullard OCP 71) were mounted on opposite sides of this disk. The pulses produced by the rotation of the disk were fed from the phototransistor into a pulse-shaping amplifier to convert the number of pulses into an average d.c. current, proportional to shaft speed, which was measured on a 270° scale microammeter (0–500 μA). Two external terminals were provided so that the meter deflexion could be conveniently checked at any time against the pulses produced by the disk. The essential features of the circuit have been described by Mitson, Griffiths & Hood (1967, Fig. 8).

3. *Calibration*

The instrument was calibrated against a wheel (56·6 cm. diameter) which could be rotated at controlled speeds by a motor and gearbox system similar to that driving the hexagon. A strip of white paper, 2 cm. high, with fine black spots (0·5 mm. diameter: Zippatone Z 315) equally spaced on it was attached to the circumference as a target. Its speed was calculated from the measured circumference by timing a given number of

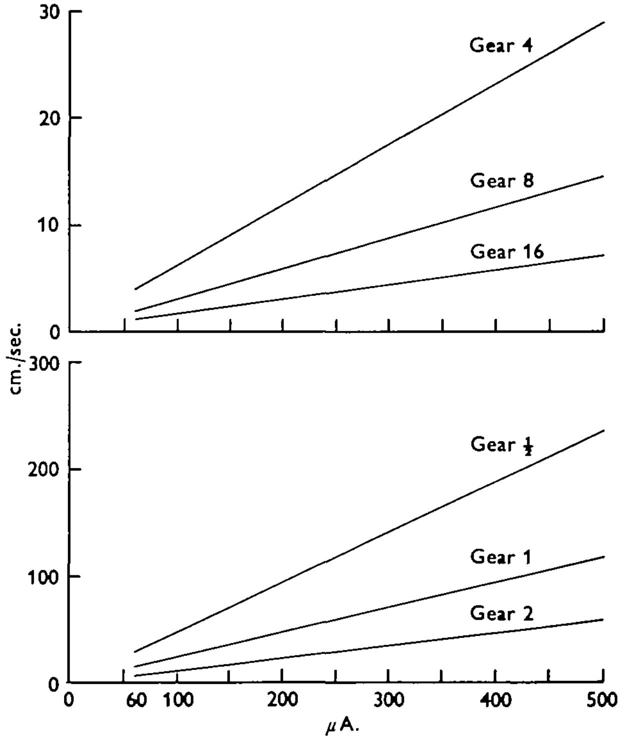

Fig. 4. Calibration curves of optical instrument.

wheel revolutions with a stopwatch. The calibration curves for six gears of the instrument are given in Fig. 4; the lowest gear was not used. A series of ten measurements made against the calibration wheel at two points on each gear showed that the accuracy of gear 16 was better than ± 1 % and that of the higher gears better than ± 0·5%.

4. *Measurement*

The instrument was mounted on the table with vertical adjustment on the instrument carriage, so that water velocity could be measured at any depth. Attention was confined to a small vertical segment by the use of slotted plates clamped against the outside wall of the flume. The slots were 7·5 cm. long and 0·5 cm. high. Separate plates were used for slots centred at even numbers from 2 to 30 cm. and odd numbers from 1 to 9 cm.; a third plate was used for measurements close to the flume floor with slots centred at 0·5, 1·5 and 2·5 cm.

Nieuwenhuizen (1966) has shown from equation (1) that the image seen in the telescope can never completely stand still as each face of the optical glass section comes round but must oscillate slightly. This was observed at slow rotational speeds but the oscillating appearance was quite distinct from the steady drift of the particles seen on each side of the null point. At higher speeds, when the images produced by each successive face of the rotating hexagon were no longer distinguished, this oscillation disappeared and determination of the null point was easier.

SUMMARY

1. A flume is described for producing currents of sea water for behaviour studies of marine fish. Its cross-section is 30 cm. wide × 32·5 cm. deep and the observation length is 550 cm.

2. Velocity and depth of water can be finely controlled and the maximum velocity in the level position is 69 cm./sec. with a depth of 10·8 cm. Maximum depth is 29 cm.

3. By tilting the flume the maximum velocity can be increased to 132·5 cm./sec. at a depth of 5·5 cm. with a maximum gradient of 1 in 40.

4. An instrument for measuring current velocity by an optical technique is also described. Its range is 0·8–240 cm./sec. with an accuracy of ± 1% over the range 0·8–8 cm./sec. in its lowest gear and ± 0·5% from 2 to 240 cm./sec. in the higher gears.

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Dr F. R. Harden Jones, of the Fisheries Laboratory, Lowestoft, originally suggested building a flume for studies of marine fish behaviour. The advice and help of Mr D. Mummery was invaluable in the detailed design of the apparatus.

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