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A study of the response of flatfish (Pleuronectidae) to electrical stimulation

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Direct observations on the reactions of flatfish of the Pleuronectidae to electrical stimulation were made by towing a manned sledge supporting an energised electrode array over the sea bed. The electrical stimulus was pulsed DC, ranging in frequency from 4 to 40 Hz. Involuntary muscular contractions were induced by this stimulus which caused the majority of fish to flee from the electrified zone. Reactions were classified into a few broad categories and the approximate fish size in each observed event was recorded. The results suggested that the most efficient frequency for inducing flatfish to leave the bottom is around 20 Hz, and that large fish are more strongly stimulated by an electric field than small fish; the latter being a significant demonstration under natural conditions of a theory based on aquarium experiments. Observations were made on the reactions of flatfish to a towed chain to assess its comparative efficiency in forcing fish to leave the sea bed.

Introduction

When flatfish of the pleuronectid family are alarmed their first defensive reaction is to burrow into the sea-bed, using a characteristic fluttering movement of their fins to partially cover themselves with mud or sand. Their skin pigmentation is normally adapted to blend with their surroundings, and when motionless and burrowed they are well camouflaged and relatively safe from predators. The author has observed that when threatened by objects being towed over the bottom, flatfish tend not to move until they are in imminent danger of being overrun. They swim rapidly clear of the hazard and immediately reburrow themselves in the bottom. Flatfish gears normally have a chain or rope rigged to scrape along the sea bed and disturb the fish. Some trawls (particularly beam trawls) carry considerable weights of chain requiring powerful and expensive towing vessels. Regular trawling with chains on a fishing ground might have an influence on the bottom fauna; however, there is little evidence available on which to assess the effect of continual "harrowing" of the sea bed.

Aquarium experiments with weak electrical stimulation (low electric field strength DC pulses) demonstrated that flatfish could be induced to flee from electrified zones (Stewart, 1973). This response suggested that an electric stimulus could be used as an aid to capture and might possibly replace the use of chain "ticklers" on trawls. If light weight electric "ticklers" could act as efficiently as heavy chain "ticklers" catch rates with existing gears could be maintained by using smaller, more economical vessels. The experiments described in this paper were carried out to investigate the reactions of flatfish, in their natural environment, to electrical stimulation, with a view to applying the results to the development of improved flatfish gears.

Observations were made by divers from a towed sledge which supported a pulse generating apparatus and an electrode array in contact with the bottom. Reactions to continuously and intermittently pulsed electrical stimulation and to a towed chain were studied. A wide range of pulse frequencies and amplitudes were tested to assess their relative efficiencies in stimulating fish. Observations were made on the reactions of flatfish to a towed chain to assess its comparative efficiency.

An electric field induces muscular contractions. As the frequency of a pulsed electric stimulus is increased, muscle is unable to relax in the interval between pulses and tetanus is induced. The frequency of tetanus for plaice is between 15 and 20 Hz. Clearly a tetanising stimulus will inhibit normal swimming and be inefficient in forcing fish to leave the bottom. An interrupted stimulus will give the fish an opportunity to take evasive action. Initially, therefore, this form of stimulus was used in the experiment, found effective, and studied at length.

The electric field distribution produced by electrodes of a finite size in an unbounded medium like the sea is highly non-uniform, with the zone of high electric field strength concentrated near the electrodes (Stewart, 1975a). Fish distributed randomly in the path of the electrodes will experience electric field strengths within a wide range, and to build up an accurate picture of fish reaction to any given stimulus it was anticipated that a large number of observations would be required. The observations made on responses to a particular stimulating frequency must take account not only of a normal distribution of reaction patterns and intensities, but also of variations due to the range of electric field strengths experienced by the fish. The field strength variation experienced by the fish could be reduced by rigging electrodes at right angles to the direction of motion. Most fish would then experience the maximum available field strength. This would introduce a complication, however, as fish would tend to be herded and their reactions to electrical stimulation would be obscured. For this reason the electrodes were rigged parallel to the direction of motion and in this configuration were found to have no mechanical stimulating effect.

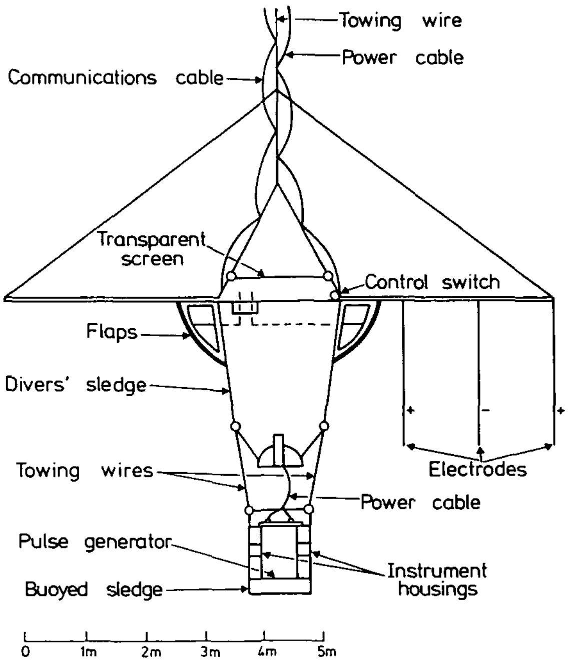

Figure 1. Plan view of towed sledge showing electrode array and pulse generator.

Apparatus and experimental procedures

General

Figure 1 is a schematic diagram of the towed sledge, pulse generator and electrode array. The sledge was towed by a 5 m launch which carried a 3 kW, 50 Hz generator to supply power to the pulse generating apparatus. The pulse generator was mounted on a separate small sledge towed astern of the main sledge. Power was supplied from the surface through a heavy flexible cable lashed to the towing rope and to the underside of the main sledge. The small sledge also carried a number of floats to reduce the weight of the pulse generator, and two small housings which contained equipment for control and monitoring. The electrodes were lengths of 1 cm diameter stainless steel warp, linked together and to the pulse generator output by heavy copper cable. The spar to which they were attached, 1 m apart, was a steel pipe encased in polythene, balanced by an identical spar lashed on the other side of the sledge. The pulse generator was controlled by a switch in a plastic box, mounted at the front of the main sledge. This switch activated a 12 V relay which supplied power to the pulse generator circuit. The circuitry of the pulse generator and the procedure used to handle the apparatus safely under water are described in detail elsewhere (Stewart and Cameron, 1974).

Two divers were required in each experimental tow. One, acting as pilot, operated the flaps and

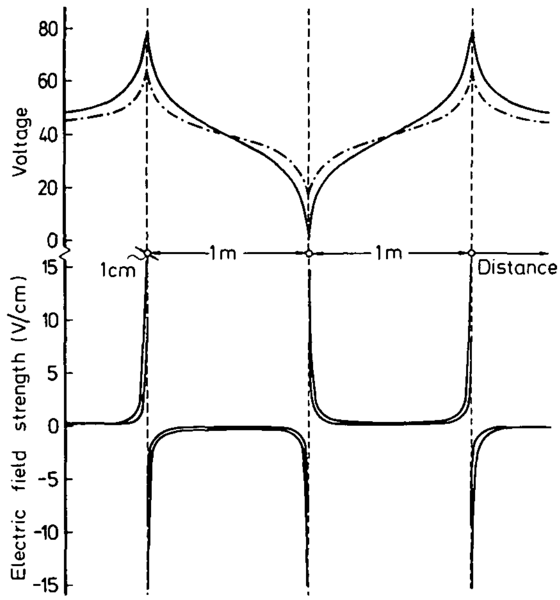

Figure 2. Electric field and voltage distribution between the electrodes.

communicated with the launch coxswain. The other, acting as observer, controlled the supply of energy to the electrodes and continuously recorded descriptions of fish reactions on magnetic tape. The pilot held the sledge a few centimetres off the bottom to give a relatively smooth ride at the towing speeds of 30 to 80 cm s^{-1}.

Electrical stimulus

The stimulus applied to the electrodes was either continuous or 1 second long bursts of exponential shaped DC pulses, with 1 second intervals between bursts, each pulse being of 4 ms duration. The pulse frequencies used were 4, 10, 20, 30 and 40 Hz, and the electrode voltages were normally 50 or 80 V. The voltage and electric field distributions in the plane of the electrodes with these voltages applied are shown in Figure 2. The generator capacity was limited and it was not possible to perform prolonged tests at voltages greater than 50 V at 30 Hz, and 40 V at 40 Hz, without damaging the generator.

Mechanical stimulus

To assess the comparative effect of a mechanical stimulus five tows were carried out with a 1 cm chain. A chain was slung on each side for balance and the

Table 1. Summary of observations of reactions of flatfish to electrical stimulation

Stimulus	Fish size*	Numbers of fish reacting: Jump and flight: Strong	Med.	Weak	Pulsations	Paralysis	Herding	No reaction	Total no. fish	Total
4 Hz	L	5	4	6	7	–	–	1	23	
50 V	M	2	12	16	20	–	–	–	50	
Continuous	S	8	26	48	48	–	–	–	130	203
4 Hz	L	22	21	11	7	–	1	2	64	
80 V	M	32	41	47	17	–	6	–	143	
1 sec. ON, 1 sec. OFF	S	19	21	67	16	–	–	–	123	330
10 Hz	L	19	24	17	24	–	2	1	87	
50 V	M	15	35	38	27	1	2	2	120	
1 sec. ON, 1 sec. OFF	S	30	59	74	27	–	2	–	192	399
10 Hz	L	2	1	1	4	–	–	–	8	
50 V	M	1	5	3	7	–	–	–	16	
Continuous	S	7	13	14	12	–	2	–	48	72
10 Hz	L	10	10	23	12	–	2	–	57	
80 V	M	27	39	38	26	–	1	–	131	
1 sec. ON, 1 sec. OFF	S	29	37	67	24	–	5	–	162	350
20 Hz	L	32	21	12	15	4	2	–	86	
50 V	M	47	48	29	11	2	4	1	142	
1 sec. ON, 1 sec. OFF	S	47	46	69	4	–	1	–	167	395
20 Hz	L	2	3	–	3	1	–	–	9	
45 V and 65 V	M	3	5	–	1	–	2	–	11	
Continuous	S	14	5	8	6	–	2	–	35	55
20 Hz	L	35	12	6	3	4	3	1	64	
80 V	M	68	49	29	14	8	4	4	176	
1 sec. ON, 1 sec. OFF	S	37	40	31	21	5	–	–	134	374
30 Hz	L	32	12	18	10	17	–	–	89	
50 V	M	58	34	47	13	12	2	–	166	
1 sec. ON, 1 sec. OFF	S	51	43	70	21	2	–	1	188	443
30 Hz	L	4	1	2	1	3	–	–	11	
80 V	M	5	4	5	2	3	–	–	19	
1 sec. ON, 1 sec. OFF	S	8	4	6	–	–	–	–	18	48
40 Hz	L	19	10	6	2	12	–	–	49	
40 V	M	29	28	22	2	15	1	–	97	
1 sec. ON, 1 sec. OFF	S	41	60	49	2	11	–	1	164	310
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* Large (L), Medium (M), Small (S).

centres of the chains trailed about 1·3 m behind the spars. The tows lasted 20 to 30 min.

Experimental area

The experiments were carried out in the southern Moray Firth in an area where the bottom is mainly sand, with scattered strips of small stones and weed. The depth in the experimental area ranged between 8 and 12 m. The flat fish seen were mainly plaice *Pleuronectes platessa*, the common dab *Limanda limanda* and the flounder *Platichthys flesus* with a few brill *Scophthalmus rhombus*, lemon sole *Microstomus kitt* and juvenile dover sole *Solea solea*.

Results

General

The observed fish reactions were classified under a few headings to simplify the process of recording underwater. The records for 64 tows are summarized in Tables 1 and 2 for electrical and mechanical stimulation respectively.

The size of each fish observed was recorded on a three point scale; those less than 15 cm being classed as small, 15 to 25 cm as medium, and over 25 cm as large. A simple method of classification was essential so that the divers could record data quickly and accurately. To achieve consistency in reporting, the bulk of the observations were made by two individuals.

Intermittent electrical stimulation

The stimulus was a one second long burst of DC pulses with a one second interval between bursts. The most common reaction produced by this stimulus was a jump off the bottom followed by swimming. The intensity of the reaction was graded on a three point scale; a strong reaction being a violent jump and fast flight; a weak reaction being a small jump and slow movement; and a medium reaction being between the two. Some fish reacted to the field but failed to leave the bottom and swim off. At frequencies below the threshold for tetanus the muscles of these fish reacted to each pulse, giving an effect similar to the normal fin flutter of a flatfish when burying itself. This was described as "pulsations". At frequencies above the threshold for tetanus the muscles were tetanised and the fish arched their backs. This reaction was described as "paralysis". At frequencies close to the threshold for tetanus fish displayed either "paralysis" or "pulsations" according to the field strength which they experienced. A herding reaction was sometimes seen, in which a fish swam either ahead of, or with, the electrodes. Very rarely, no reaction of any kind was noted. It was, however, difficult to see fish which did not move, particularly in conditions of poor visibility. In all, seven types of reaction were recorded.

Fish fleeing from the electrodes nearly always swam to starboard or astern, and rarely swam towards the sledge, suggesting that the electric field was not affecting them enough to cause disorientation or obscure their awareness of other hazards. The 50 V, 4 Hz intermittent stimulus was found to be very weak and observations were made with 50 V, 4 Hz continuous pulsing. To simplify interpretation of the data, the number of fish in each size group observed to react in a certain way has been expressed in Table 3 as a percentage of the total number of fish of that size seen whilst a given stimulus was in use.

Continuous electrical stimulation

The reactions observed depended much more critically than for intermittent stimulation on whether or not the fish were inside or outside the electrified zone. Those within the zone displayed "pulsations" or "paralysis" depending on frequency and voltage. These reactions inhibited swimming and escape until the electrodes had passed over the fish. Most of the strong reactions observed were from fish in front of the electrodes responding strongly on first experiencing the field.

Table 2. Numbers of flatfish reacting to a tickler chain expressed as a percentage of the total number of fish of each size seen to react.

Fish size	Number of fish	Escaped over	Reaction to chain: Herded, distance moved 1 m	2 m	3 m	Run over	No reaction
Large............	28	67·9	–	21·4	7·1	3·6	–
Medium..........	64	71·8	7·8	6·3	6·3	7·8	–
Small............	52	69·1	5·8	15·4	1·9	3·9	3·9

Table 3. Numbers of flatfish reacting to electrical stimulation expressed as a percentage of the total number of fish of the same size seen with the same stimulus in use.

Stimulus	Fish size*	Percentage of fish reacting							Total no. fish	Total
		Jump and flight			Pulsations	Paralysis	Herding	No reaction		
		Strong	Med.	Weak						
4 Hz	L	21·8	17·4	26·1	30·4	–	–	4·3	23	
50 V	M	4·0	24·0	32·0	40·0	–	–	–	50	
Continuous	S	6·2	20·0	36·9	36·9	–	–	–	130	203
4 Hz	L	34·4	32·8	17·2	10·9	–	1·6	3·1	64	
80 V	M	22·4	28·6	32·9	11·9	–	4·2	–	143	
1 sec. ON, 1 sec. OFF	S	15·5	17·1	54·5	13·0	–	–	–	123	330
10 Hz	L	21·8	27·6	19·5	27·6	–	2·3	1·2	87	
50 V	M	12·5	29·2	31·6	22·5	0·8	1·7	1·7	120	
1 sec. ON, 1 sec. OFF	S	15·6	30·7	38·6	14·1	–	1·0	–	192	399
10 Hz	L	25·0	12·5	12·5	50·0	–	–	–	8	
50 V	M	6·3	31·2	18·7	43·8	–	–	–	16	
Continuous	S	14·6	27·1	29·2	25·0	–	4·1	–	48	72
10 Hz	L	17·5	17·5	40·4	21·1	–	3·5	–	57	
80 V	M	20·6	29·8	29·0	19·8	–	0·8	–	131	
1 sec. ON, 1 sec. OFF	S	17·9	22·8	41·4	14·8	–	3·1	–	162	350
20 Hz	L	37·2	24·4	14·0	17·4	4·7	2·3	–	86	
50 V	M	33·1	33·8	20·4	7·8	1·4	2·8	0·7	142	
1 sec. ON, 1 sec. OFF	S	28·0	28·7	41·3	2·4	–	0·6	–	167	395
20 Hz	L	22·2	33·3	–	33·4	11·1	–	–	9	
45 V and 65 V	M	27·2	45·5	–	9·1	–	18·2	–	11	
Continuous	S	40·0	14·3	22·9	17·1	–	5·7	–	35	55
20 Hz	L	54·7	18·7	9·4	4·7	6·2	4·7	1·6	64	
80 V	M	38·6	27·8	16·5	8·0	4·5	2·3	2·3	176	
1 sec. ON, 1 sec. OFF	S	27·6	29·9	23·1	15·7	3·7	–	–	134	374
30 Hz	L	36·0	13·5	20·2	11·2	19·1	–	–	89	
50 V	M	34·9	20·5	28·3	7·9	7·2	1·2	–	166	
1 sec. ON, 1 sec. OFF	S	27·1	22·9	37·2	11·2	1·1	–	0·5	188	443
30 Hz	L	36·3	9·1	18·2	9·1	27·3	–	–	11	
80 V	M	26·3	21·1	26·3	10·5	15·8	–	–	19	
1 sec. ON, 1 sec. OFF	S	44·4	22·2	33·4	–	–	–	–	18	48
40 Hz	L	38·8	20·4	12·2	4·1	24·5	–	–	49	
40 V	M	29·9	28·9	22·7	2·1	15·4	1·0	–	97	
1 sec. ON, 1 sec. OFF	S	25·0	36·6	29·9	1·2	6·7	–	0·6	164	310
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* Large (L), Medium (M), Small (S).

Mechanical stimulus

When the 1 cm chain was towed over the bottom the reaction most frequently seen was a quick jump back over the chain (see Table 2). Once over the chain the fish settled on the bottom, and few fish swam as far or as fast as those stimulated by the electric fields. Herding reactions were also seen and are classified according to the distance herded. The chain became clogged with weed and ran over crustaceans and some fish.

The mechanical effect of the electrodes is also of importance and one tow was conducted without an electric field to check on the mechanical tickling effect of the electrodes. Only two fish were observed to move when touched by the electrodes, a significantly lower number of observations than in the electrified tests. On other occasions with the power switched off, the electrodes were seen to touch fish without causing them to move. As far as could be ascertained the electrodes caused negligible damage to the bottom.

Reactions of other species

(i) Roundfish. Most roundfish encountered were small gadoids. On experiencing the field, these displayed either tetanus or pulsations and escaped rapidly in apparently random directions.

(ii) Sandeels (*Ammodytes* spp). The experimental area contained large numbers of this species and an electric stimulus readily forced them out of the bottom. The 40 Hz stimulus induced tetanus which held the sandeels rigid in swimming positions for the 1 second duration of the burst.

(iii) Razor shells (*Ensis* sp). At 30 Hz and above, a prolonged stimulus (eg if the sledge was stationary for electrical tests), induced this species to emerge from the bottom.

(iv) Brown shrimps (*Crangon crangon*). The area was sparsely inhabited by brown shrimps. With the 4 Hz continuous stimulus the jumping behaviour described by de Groot and Boonstra (1970) was observed.

Discussion

Reliability of data

The value of any conclusions drawn from this experiment is dependent on the accuracy with which the divers recorded their observations. Inevitably there will be some variation in classification between individuals, and for each individual on different occasions. There may also have been a tendency to underestimate the number of small fish, as these were difficult to see when their movements were slight, particularly when the visibility was low. An estimate of the accuracy of classification would be useful, and it is possible to obtain comparative data on size classification from catch statistics. In Figure 3 cumulative length distributions for the catches in three hauls carried out in July 1974 in the experimental area are shown. The catch distributions are for the non-electrically stimulated catches recorded during a comparative fishing experiment with a divided gear (Stewart, 1975b).

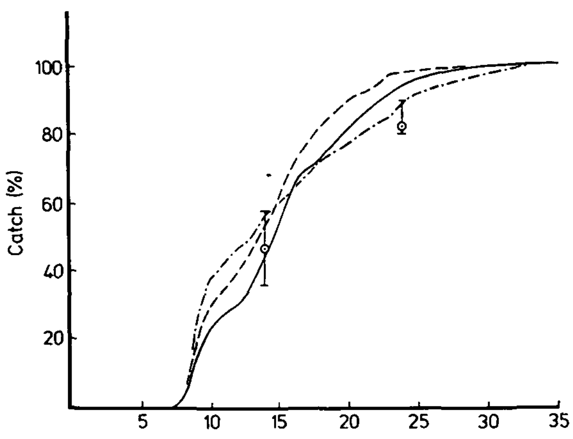

Figure 3. Cumulative fish length distributions for 3 hauls in the experimental area, with divers' size classifications shown.

The divers classified fish below 14 cm as small, 15 to 24 cm as medium and 25 cm and over as large. Summing the observations for each size group in Table 1 shows that 46% of the fish observed were less than 14 cm, and 82% were less than 24 cm. These mean values are shown in Figure 3 with the range covered by the records of all the observers. The divers' size classification is in fair agreement with the catch length distributions suggesting that the data are a reasonable basis for assessing the relative effectiveness of the range of stimuli tested.

Electrical stimulation of flatfish

The experiment has demonstrated that an electrical stimulus is efficient in inducing flatfish to leave the bottom. Both continuous and intermittent stimulalation are effective, but it was considered that the continuous stimulus, which appeared to be more intense, would be less effective if used on a fishing gear. The two reactions produced by the continuous stimulus which make it unsuitable are the rapid flight from in front of the electrodes and the tendency to remain on the bottom, in a state of temporary "shock", after pulsating or being tetanised. The reactions described as "pulsations" and "paralysis" are involuntary but the flight reactions are a response to the disturbing or irritating effect of the electric field. The results show that stimuli with frequencies above the threshold for tetanus (15 to 20 Hz) produced a greater percentage of strong reactions. "Paralysis" was increasingly evident at frequencies of 20 Hz and over, and the incidence of "pulsations" fell as the frequency rose; both results being as expected. Herding reactions were rarely seen, particularly at the higher frequencies. The absence of herding behaviour may be due to there being no part of the electrodes rigged at right angles to the direction of motion. Very few fish failed to react, but since stationary fish were difficult to see, it cannot be concluded that almost every fish reacted. It is possible to draw some conclusions about the relative effectiveness of the various forms of stimulus. The reaction most often seen was a jump followed by swimming. As the frequency is increased there is a trend from a majority of weak reactions to a majority of strong reactions. The greatest percentage of strong reactions was recorded at 20 Hz, 80 V. It is possible that at the higher frequencies the increasing strength of the stimulus, which produces more "paralysis" reactions, tends to inhibit flight in some fish. Comparison of the high and low voltage records for each frequency shows that increasing the voltage tends to increase the percentage of strong reactions. It should be noted that there are limited data for the 30 Hz, 80 V case, and that the 4 Hz, 50 V case, being for a continuous stimulus, includes more strong reactions than would be seen with a 4 Hz, 50 V interrupted stimulus.

The records show that in most cases a greater percentage of large fish exhibited strong reactions than small fish, and that a greater percentage of small fish exhibited weak reactions than large fish. This is the only experimental evidence collected to date by the author which shows a size dependence in the intensity of reaction, and is a significant result as it shows that an electric stimulus can be size selective. For those species of roundfish whose responses to electric fields have been investigated in aquarium conditions it has been found that large fish react at lower field strengths than small fish (Bary, 1956). The reactions of flatfish have not been studied in this way, but there is no reason to suppose that electric fields effect them in a different manner.

The electric field distribution in Figure 2 shows that the high field zone is concentrated close to the electrodes, and the region of maximum intensity is only 30 cm wide. Between each pair of electrodes there is a region 70 cm wide with relatively low and nearly uniform field strength, 30 Vm^{-1} and 18 Vm^{-1} approximately for the 80 V and 50 V cases respectively. Bary (1956) has also reported fish detecting electric field strengths as low as 18 Vm^{-1}. The electric field in the intense zone will be averaged out over the bodies of the fish, thus reducing the apparent peak intensity of the stimulus.

Mechanical stimulation

The reaction of fish to the towed chain was much as expected. It is also efficient in inducing flatfish to leave the bottom although an electric stimulus can induce a more rapid escape reaction.

Applications

The consistency with which fish and shellfish were induced to move by the electric stimulus suggests that it could be useful in surveying areas for flatfish, bottom dwelling shrimps and sandeels. Observations could be made by sonar or underwater TV.

Electric ticklers could be used in place of chain ticklers on trawls to force flatfish off the bottom. De Boer (1969) has measured the drag forces generated by chain ticklers on a beam trawl towed by a 540 h.p. vessel. He found that at maximum towing speed 20% of the total gear resistance was contributed by the friction of the chains on the sea bed. Allowing for vessel drag, the chain resistance was absorbing an estimated 80 h.p. of engine output. To electrify the area covered by the chains on this beam trawl would require a mean power of about 4 h.p., but the surge currents demanded by a large pulse generator might require a source capacity of up to 10 h.p. Replacing chain ticklers by electric ticklers would not necessarily increase the catch-rate, but should permit smaller engined vessels, consuming less fuel, to maintain catch-rates with a given size of gear.

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