THE ROLE OF SOUND IN THE BRITISH COLUMBIA TROLL SALMON FISHERY

by

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ABSTRACT

Sparked by anecdotal accounts of boat noise influencing the catch rates of commercial salmon trollers on the B.C. coast, acoustical studies of both boats and fish were undertaken. The study was in four parts:

1. Acoustical output of salmon trollers: Recordings were made of troll vessels and examined on a spectrum analyzer. Sonic output was predominantly of low frequency, under 300Hz. Output levels at trolling speed (1-2m/s) were about 20dB re 1μbar at 1meter from the hull. Higher frequency spikes (1-2.5kHz) were observed with operation of hydraulic pumps for auxillary equipment. Broadband, transient output (approximately 1-6kHz), was thought to be correlated with cavitation from propellors.

2. Fish sounds: Recordings were made of herring, salmon and rainbow trout swimming rapidly and feeding on pellets in net pen enclosures. These were examined on a spectrum analyzer. Two types of sounds were evident, "knocks" and "scratches". Knocks were correlated with rapid swimming and maneuvering and are likely of hydrodynamic origin. Scratches were thought to be produced by branchiate and skeletal movements and were relatively faint. Knocks were 1-2kHz, scratches 3.5-5.5kHz. The dominant sounds in actively feeding, subsurface salmonids, were knocks. Recordings of feeding schools sounded remarkably like trickling water to the human ear.

3. Attracting salmon in net pens: Attempts were made to lure coho (*Oncorhynchus kisutch*) and chinook (*Oncorhynchus tschawytscha*) as well as rainbow trout (*Salmo gairdneri*) to a speaker projecting recorded feeding sounds of the target fish. No responses of any kind were observed to output levels as high as 55dB re 1μbar at 1meter.

4. Attracting salmon at sea: Recorded and simulated feeding and swimming sounds of salmonids were projected within the gear array of a commercial salmon troller fishing on the west coast of Vancouver Island, B.C. Catch rates were monitored with the test sounds on and off. Output level was 55dB re 1μbar at 1meter. No significant change in catch rate was observed in response to the test sounds.

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1.0 INTRODUCTION

1.1 JUSTIFICATION

There are about 2200 vessels that fish for Pacific salmons (*Oncorhynchus* spp.) on the British Columbia coast by means of troll gear. In the past coho (*O. kisutch*) and chinook (*O. tschawytscha*) were the principal target species of this fleet but declining stocks of these fish have redirected effort to pink (*O. gorbuscha*) and to a lesser extent sockeye (*O. nerka*) and chum (*O. keta*) salmon. Trollers fish primarily in outside waters from the Washington border to Dixon entrance as the fish must be actively feeding for capture by this gear and salmon generally forego food as they approach their parent stream. Troll vessels use artificial lures and baits rigged to roll, flutter or dodge as they are pulled through the water at 1-2 m/s. A high degree of skill is required in the preparation and presentation of lures, particularly to larger, older coho and spring salmon to tempt them to bite. The basic fishing rig of a troller is shown in Fig.1-1, while some lures are shown in Fig.1-2.

Anecdotal evidence suggests that sound has an influence on the catch rate of trollers. Experienced fishermen believe that components of the boats drive train and steering gear can affect fishing success. Care is taken to ensure that engine and shaft alignment is true and that intermediate and stern bearings are tight and well lubricated. Propellers are examined regularly to ensure they are undamaged and balanced. Many trollers prefer a four bladed propeller to a three bladed

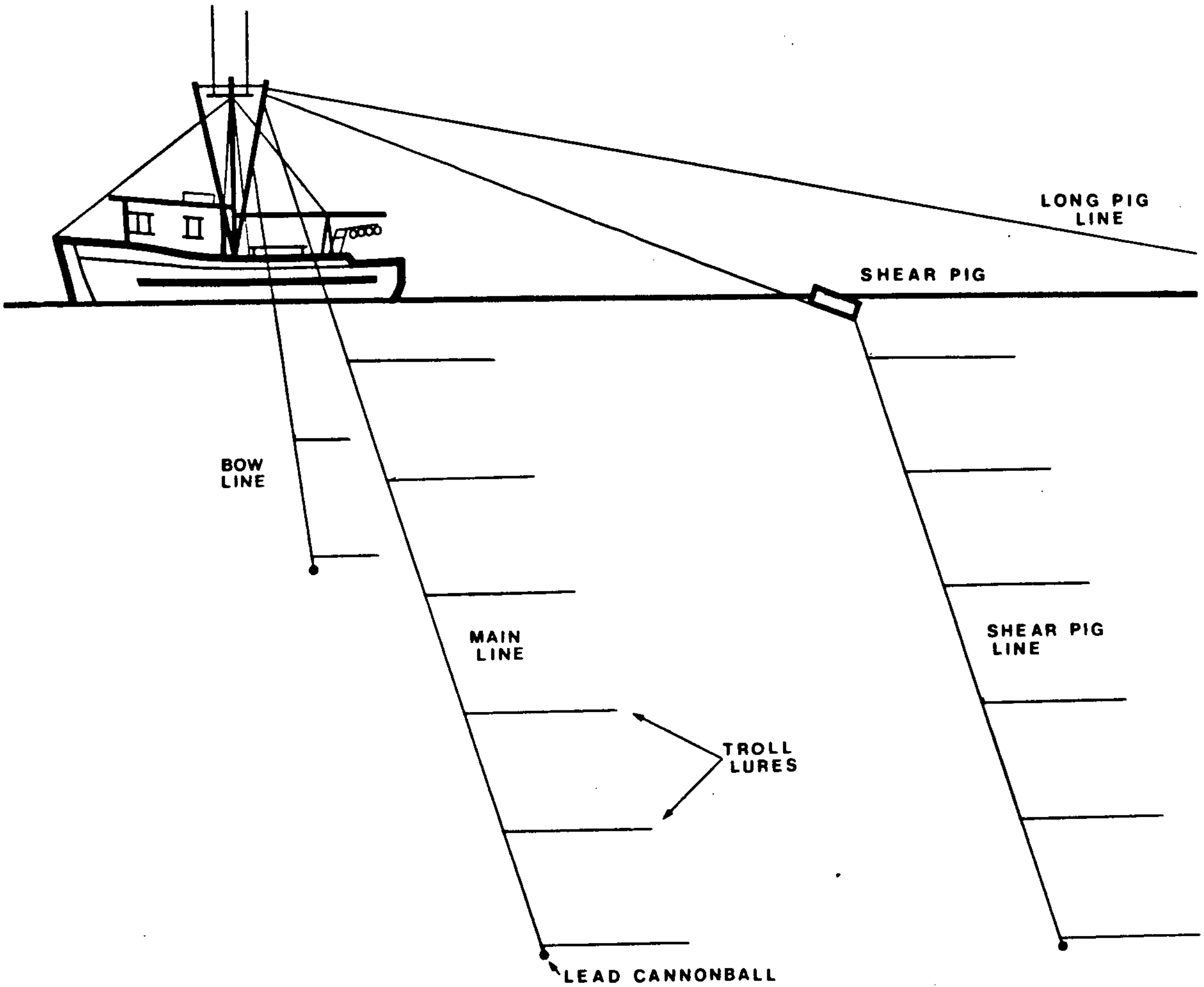

FIGURE 1-1. The standard gear array of a B.C. salmon troller. The vessel fishes two of each line shown, a set from each pole.

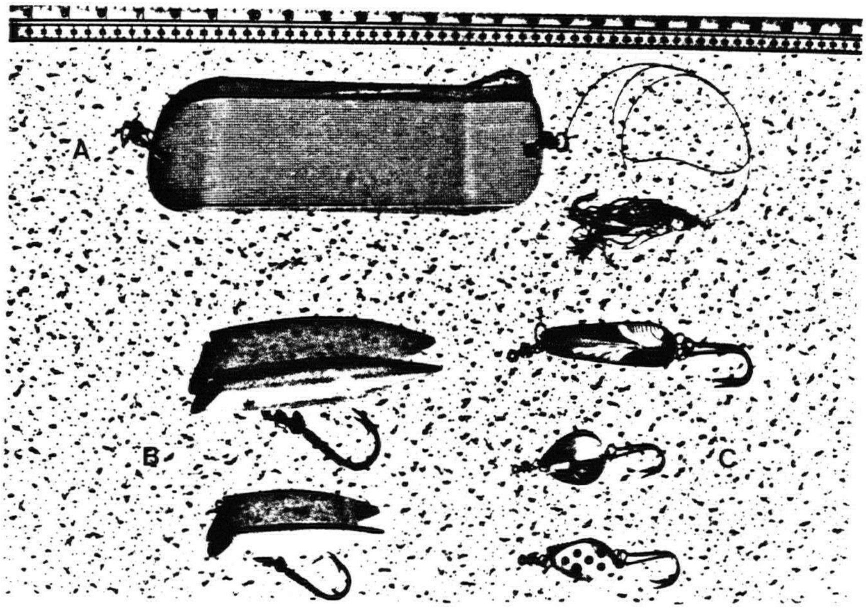

FIGURE 1-2. Some terminal lures used in the British Columbia troll salmon fishery. A. Flasher and hootchie. B. Plugs. C. Spoons.

one, feeling they are quieter and thus "fishier". Tight rudder stock bearings are also thought necessary for best results. Some trollers feel that gas engines fish better than diesels because of smoother, quieter performance. Often, fishermen monitor the catch rate of the lures closest to the boat as an index of their vessels sonic performance. There is no agreement whether these precautions guard against production of repulsive sounds or ensure output of attractive ones. The range of alternative explanations for a boat with the "right" sounds outfishing one with the "wrong" sounds include:

1/ An increase in the propensity of fish, otherwise aware of the gear, to attack it through association of the boat sounds with a feeding opportunity. This might be due to similarities between boat sounds and baitfish or feeding sounds.

2/ An increase in the area of influence of the gear; that is, fish that would not otherwise have sensed the gear's presence becoming aware of it by homing on the sound source.

3/ both of the above.

4/ Absence of frequencies or patterns in the boat's sonic output that cause inhibition of feeding activity amongst fish in the path of the gear. Such sounds might resemble those of salmon predators.

5/ Absence of frequencies or patterns causing active repulsion of fish from the vicinity of the gear before they can otherwise sense it's presence.

6/ Both 4 and 5.

The feeding behavior of salmon at sea suggest that sound may be important in prey location and capture. Spring salmon in particular, but also coho, are often taken at considerable depths (100fathoms). These salmon feed primarily on small schooling species such as herring (Clupea harengus), and sand lance (Ammodytes hexapterus). In the turbid coastal waters of B.C. light penetration is restricted by dense phyto and zooplankton blooms in the "mixed layer" as well as suspended material from runoff. This is particularly so in the spring and summer. Salmon often feed most actively at dawn and dusk when the light field is further attenuated. Vision can be useful only at short range under these conditions. Considerable turbulence is also a feature of coastal waters, as a result of tidal (5-8m range) and wind generated currrents driving water masses across rugged underwater topography (Thompson 1981). Thus the fishes olfactory sense is likely unreliable directionally for lack of a smooth concentration gradient. Another common observation of troll fishermen is that catch rates often suddenly increase (and subsequently decrease) over a large area (20 nautical miles or more) almost instantaneously; the fish "come on the bite" in the jargon. The occurrence of this phenomenon is established through radio communication between boats. Periods of high catch rate are often associated with high and low slack water in inshore waters, however tidal currents over offshore banks do not stop, then reverse direction in a simple manner (Thompson 1981). Further, such periods often occur at the same time each day for several weeks in certain areas (Boyes pers. obs.) while tidal cycles advance an hour or so each day. Acoustical stimuli may be responsible for the transmission of this "feeding frenzy effect" over these distances in such a short time. Although concrete evidence for Pacific salmon responding to sound is lacking, there are many accounts of other fish, particularly predatory species, doing so. Examples are found in the following section.

1.2 LITERATURE REVIEW

Man has long used sound for attracting, and frightening fish in order to catch them. Accounts on fish responding to sound can be found in the works of Aristotle and Pliny (cited in Moulton 1963). Parker (1918), von Frisch (1936), Kleerekoper and Chagron (1954), Moulton (1963, 1964), Protasov (1965), Tavolga (1971), Popper and Fay (1972), and Hawkins (1973) have reviewed the modern literature. Sounds that attract (or repel) fish must have significance, either learned or innate, to the animal. Usually there is an association with feeding or reproductive behavior. Hook and line fisheries require sounds that represent feeding opportunities to target fish. These are most often in the form of prey sounds or the characteristic noises of attack and feeding behavior by predators. Following are a number of examples from the literature of acoustic attraction or reaction in a variety of fish both captive and wild.

Moulton (1960) played recorded sounds of the engraulid (*Anchoviella choerstoma*) to young, captive jacks (*Caranax latus*), a natural predator of the anchovy. The jacks showed "quickened swimming movements of a non-directional type". Playback to _C. latus_ of its own pharyngeal tooth rasps "appeared to initiate feeding reactions" and resulted in the jacks actually nibbling at the transducer. Habituation to the stimulus was apparent after a few minutes.

Sharks have been known to appear as if from nowhere during fishing operations where there are wounded, struggling fish on lines or in nets. It appears that an ability to perceive and home on sounds from this activity allows them to do this. Studies by Hobson (1963), Nelson and Gruber (1963), Nelson (1967), Banner (1968, 1972), Nelson _et al_ (1969), Myreberg _et al_ (1969, 1975, 1978), Myreberg (1972), and Nelson and Johnson (1972, 1975) have shown that a variety of sharks in both the Atlantic and Pacific are attracted to sources of pulsed low-frequency sound. These may be the recorded sounds of struggling or rapidly swimming fish or simulations electronically generated. Nelson and Johnson (1975) observed that resident sharks in Rangiroa atoll, near Tahiti responded quickly and directionally to the sounds of speared, struggling reef fish from several hundred meters away. The sharks eventually came to associate the noise of a discharging speargun with a possible meal whether or not a fish was hit.

Hashimoto and Maniwa (1966, 1971), and Maniwa (1975), have had success in attracting carp, yellowtail, mackerel, sea bream, squid and even crab (no species names given) with playbacks of sounds these animals make during feeding. Carp could also be attracted simply by "tapping the side of a boat with a piece of stick".

Steinberg et al (1965), using an underwater video camera monitoring a speaker noted that yellowtail snappers (Ocyurus chrysurus) were consistently attracted to a source of pulsed 20Hz signals.

Iverson (1966, 1967), conditioned captive yellowfin tuna (Thunnus albacares) and false albacore (Euthynnus affinis), to a food reward upon playing a pure tone stimulus. A sudden noise or a rapid increase in volume of a signal elicited speedy withdrawal from the source and it is suggested that sound might thus be used to hold tuna in a seine while the net is closed and pursed.

Richard (1968), using remote video monitoring of an underwater speaker near Bimini, Bahamas, was able to attract and identify eight species of teleosts and three species of shark. Pulsed, pure-tone signals, 25-50Hz were the stimulus. Notably, only demersal predatory fish were attracted although herbivorous reef fish were common around the test site.

York (1972) has demonstrated attraction of skipjack (Katsuwonus pelamis) and albacore (Thunnus alalunga) to sounds of surface schooling anchovies (Engraulis australis). It was found that the splashing sounds of the anchovies and the diving birds (gannets, Sula bassana serrator and shearwaters, Puffinus gavia gavia), preying on them were the predominant component of the attractive recordings.

Chapman (1975), showed that three species of piscivorous teleosts, the cod (Gadus morhua (L.)), the saithe (Pollachius virens (L.)) and the lythe (Pollachius pollachius (L.)), resident in Loch Torridon, Scotland, could be attracted by low frequency pure-tone stimuli. The fish also developed a strong positive response to the sounds of divers open-circuit scuba gear. This was thought to be associated with the stirring up of feed by the divers activities on the bottom.

Erickson (1979), found a relationship between the acoustic spectrum of albacore trollers and their catch rate. Analysis of vessel recordings with respect to within fishing group relative catch rates brought out a negative correlation between fishing success and sound output above 1500Hz. Spectrum peaks above this frequency were attributed to worn or dry propeller shaft bearings, damaged propellers and in one case a supercharger. It is interesting to note that albacore fishermen, like salmon trollers, have long held that boat and gear sounds influenced catch rates (the boats electrical output was thought to be important also - see Nomura 1980), but that this study is the first to substantiate it.

There are few accounts in the literature of salmonid response to sound. As far as I am aware only three relate to Pacific salmons. Disler (1960) observed that fingerling chum salmon "perceived the direction of a source of vibrations caused by thumping on the ground at a distance of 1.5-2meters". VanDerwalker (1966), reviewed some attempts to guide down migrating rainbow (Salmo gairdneri) and brown (S. trutta) trout, and chinook salmon past turbine intakes with sound fields. Startle reactions to low frequencies (up to 280Hz) could generally be obtained but rapid habituation was apparent, even at very high sound intensities (82dB re 1μbar). Stober (1969), investigated sounds made by cutthroat trout (_Salmo clarki_) and their response to playback of these sounds. The predominant sound made was a "thump", associated with a sudden tail beat. The principle frequency of a thump was at 150Hz. Cutthroat were shown to hear up to 650Hz, with a threshold of -35dB re 1μbar at 150Hz. Relatively high ambient and equipment noise makes the threshold level and maximum frequency uncertain. Abbott (1972), conditioned pond reared rainbow trout to feed at the source of a 150Hz pure tone. About 90% of the fish were conditioned after 45 trials. The fish responded to a 300Hz tone but not to a 600Hz tone. Kol'tsova _et al_ (1977) using both conditional reactions and electrophysiological monitoring of inner ear potentials, produced a frequency-threshold curve for the pink salmon. They found that the fish responded to frequencies from 30-2600Hz. Hawkins and Johnstone (1978), studied the hearing of the Atlantic salmon (_Salmo salar_) by means of a cardiac conditioning technique and obtained a threshold curve showing sensitivity between 30-400Hz.

If salmon use sound in prey location and capture, the noises of prey species and of the salmon themselves are of interest. The sounds that fish make have been grouped into three categories by Tavolga (1964). These are: stridulatory - produced by hard parts such as denticles, teeth, fin rays and bones being rubbed or scraped against one another; hydrodynamic - swimming sounds resulting from undulatory propulsive and turning movements, flow turbulence and associated internal sounds; swim bladder - sounds associated with gas transfer to and from the gut or with muscular contractions effecting rhythmic compression of the bladder.

A principal prey species of coho and chinook salmon is the herring which occurs in large schools on the B.C. coast. The sounds produced by herring include; eating noise, a stridulatory sound from jaw and operculum movement (Shwartz pers.comm.); hydrodynamic sounds, knocks or thumps from rapid acceleration or veering (Fish 1980, Boyes pers.obs.); and croaks, likely resulting from swim bladder to gut gas transfer (Boyes pers. obs., Shwartz pers. comm.). Probably the loudest sounds from a school of herring under the attack by predators are the hydrodynamic or swimming noises associated with "streaming" (coordinated movement of the school) and "veering" (rapid simultaneous change of direction of the school). Moulton (1960), found this to be the case with large schools of anchovies, of similar size to a herring, under attack by predators. Here, veering sounds were the most intense and were centered in the frequency band 500-1500Hz.

There has been little work done on the sounds of Pacific salmon and only one paper on hearing thresholds appears in the literature. Neproshin (1971, 1974), and Neproshin and Kulikova (1975), have studied the acoustic behavior of sockeye, pink, coho and chinook on the spawning grounds. They found that salmon make at least nine distinct sounds, fitting into all three of Tavolga's (1964), categories. The loudest were drumming sounds, measured at about 40dB re 1μbar (see Table 1-1 for sound unit conversions) and thought to be produced by muscular contractions of the swim bladder. Hydrodynamic sounds were associated only with fish breaking the surface and could not be detected from the movements of submerged fish. Ambient noise levels are not given but are likely quite high as salmon spawn in running water, thus masking may account for the absence of swimming sounds. The sole reference to the hearing ability of Pacific salmon is the Kol'tsova et al (1977) paper on the pink salmon. The very wide range of frequency discrimination reported (30-2600Hz), contrasts with those determined for fish of a similar form and auditory morphology such as the Atlantic salmon (30-400Hz). Extrapolation of these results to other Pacific salmon, particularly the coho and spring salmon targeted by trollers must therefore be cautious.

1.3 THE MORPHOLOGY AND ACUITY OF HEARING IN FISH

Although there has been little work done on the audition of Pacific salmons, much information exists on the hearing of other fish. The inner ear of teleost fish is generally homologous to that of mammals, having three semi-circular canals and three or more otoliths. There is considerable structural variation between species: reviews of fish labyrinth morphology include Grasse (1958), Moulton (1963), and Lowenstein (1971).

The superorder Ostariophysi (families Cyprinidae, Characinidae, and Siluridae), have a smaller and more complex saccular otolith relative to the lagenar otolith and an endolymphatic connection between the two (the transverse canal), not seen in other species (Moulton 1963). The Ostariophysi further have a direct connection between the swim bladder and inner ear via the Weberian ossicles. This link is thought to account for the acute hearing of these fish, the swim bladder acting as a resonator and transmitting vibrations to the inner ear (Poggendorf 1952, Kleerekoper and Roggenkamp 1959). Audiograms of three ostariophysan fish appear in Fig.1-3 illustrating the wide range of sensitivity and low thresholds generally found in this group. A number of other fish seem to have swim bladder-inner ear connections of one kind or another (see the review of Hawkins 1973), and experimental evidence suggests that many of these have relatively good hearing.

Non-ostariophysan fish lacking an alternative method of swim bladder-inner ear linkage, or lacking a swim bladder entirely such as the Elasmobranchii generally have poor hearing, with restricted frequency range and high thresholds. Fig.1-4 shows audiograms for the lemon shark (Negaprion brevirostris), the pink salmon and the Atlantic salmon. As noted in section 1.2, the high frequency discrimination (above 1000Hz or so) reported for the pink salmon by Kol'tsova et al (1977) is a surprising result and may be artificially high as a result of the experiments being done in a small tank (Parvulescu 1964, Hawkins and Maclennan 1975). Audiograms for the yellowfin and

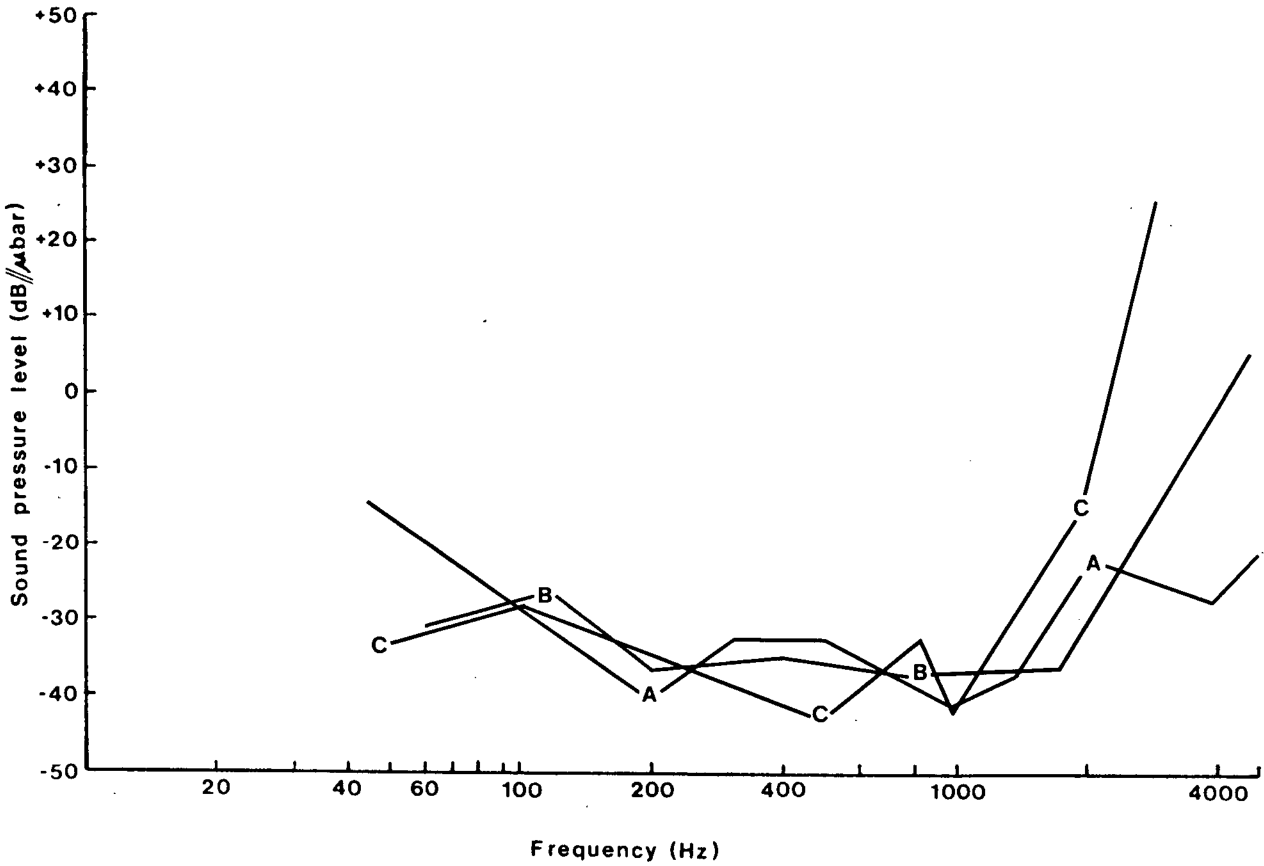

FIGURE 1-3. Auditory thresholds of three ostariophysine species. A/ Mexican cave fish (*Astyanax mexicanus*), Popper 1970. B/ Catfish (*Ictarulus nebulosus*), Poggendorf 1952. C/ Carp, (*Cyprinus carpio*) Popper 1973.

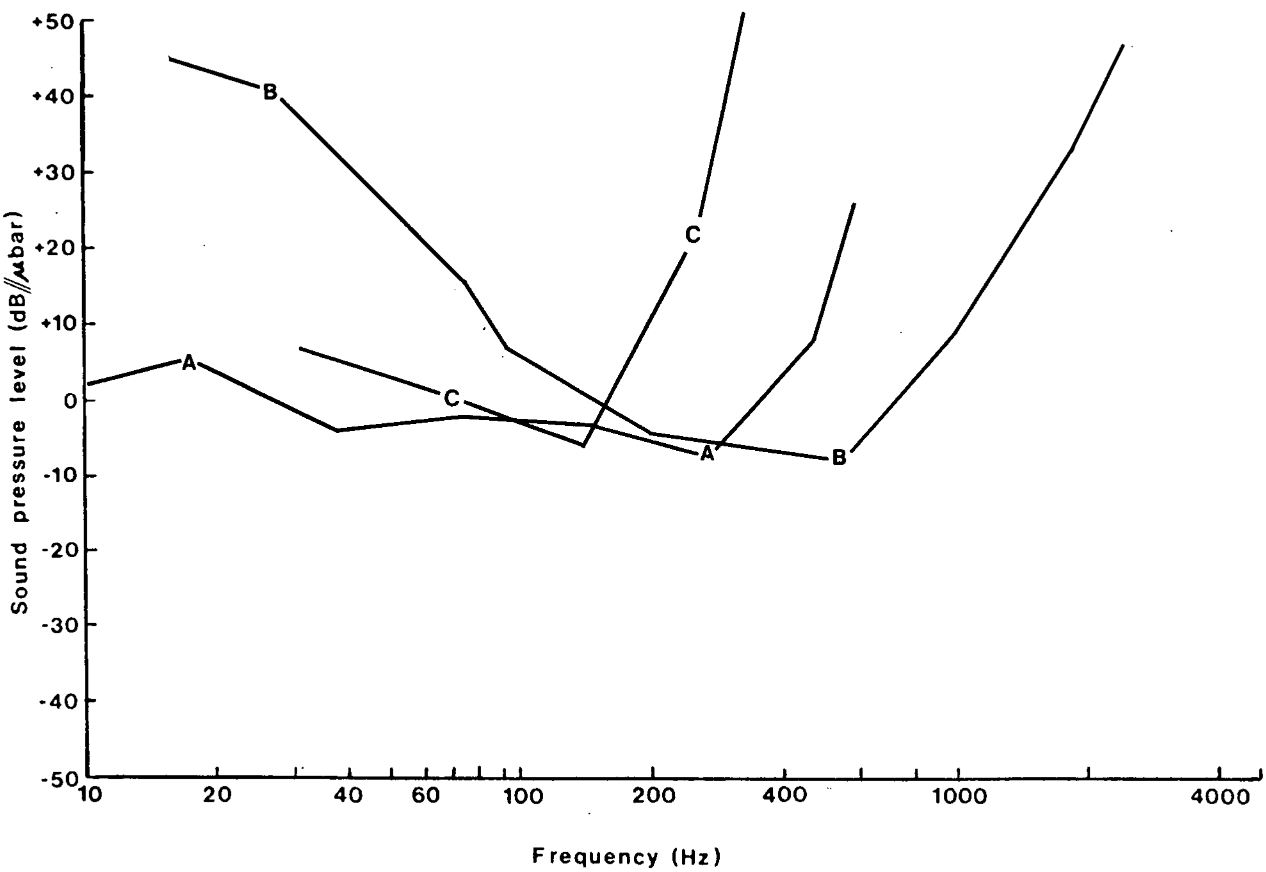

FIGURE 1-4. Auditory thresholds of three non-ostariophysine species. A/ Lemon shark, (Negaprion brevirostris), Banner 1967. B/ Pink salmon, (Oncorhynchus gorbuscha), Kol'tsova et al 1977. C/ Atlantic salmon, (Salmo salar), Hawkins and Johnstone 1978.

false albacore tunas and for the cod appear in Fig. 1-5. Again, the range is narrow and threshold high for these non-ostariophysans. It is interesting to note that relatively large, piscivorous fish tend to hear less well than smaller herbivorous species, particularly reef dwellers.

Because sound is relatively well transmitted in the sea, background noise (see section 1.4) is a constant feature of the ocean environment. A fish's ability to perceive an important sound over or through this background is therefore vital to its ability to utilize sonic information in capture of prey, avoidance of predators etc. A review of the work on auditory masking and the critical band concept in fish is found in Tavolga (1974). Fish with good hearing, the ostariophysi and others with the swim bladder-inner ear linkage have good frequency discrimination and thus a narrow critical band. Non-ostariophysian fish generally display poor frequency discrimination but attempts to measure a critical band have been unsuccessful (Tavolga 1974). Surprisingly, for the few species tested, signal to noise ratios appear to be in the same range for both ostariophysian and non-ostariophysians, 20-22dB with broadband noise (Buerkle 1969, Chapman and Hawkins 1973, Tavolga 1974).

Directional hearing in fish is currently an area of active experimentation and much theoretical debate. A review of the older literature is found in Moulton and Dixon (1967). While many early experiments, usually in tanks or ponds, failed to demonstrate directional discrimination in conditioned fish,

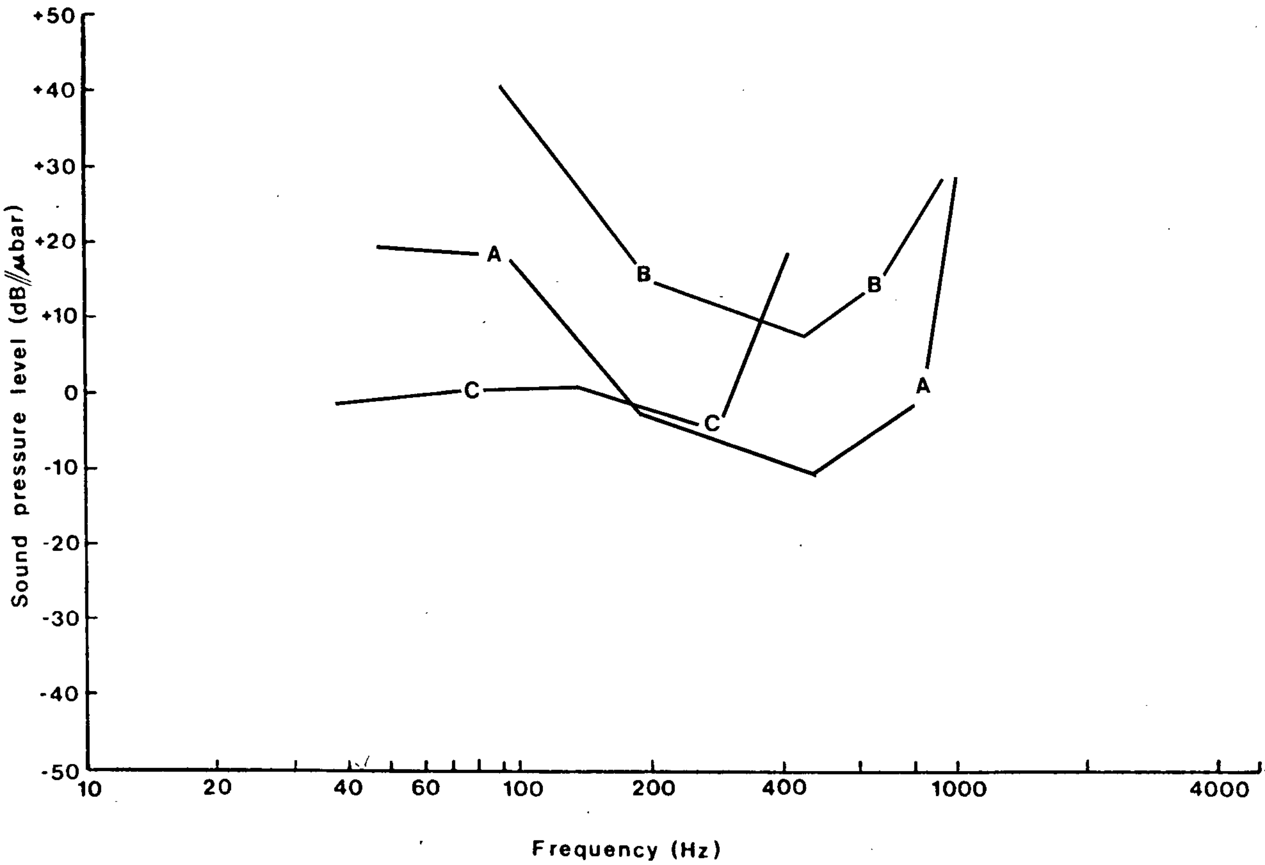

FIGURE 1-5. Auditory thresholds of three non-ostariophysine species.
A/ Yellowfin tuna, (Thunnus albacores), Iverson 1966.
B/ False albacore, (Euthynrun affinis), Iverson 1967.
C/ Cod, (Gadus morhua), Buerkle 1967.

more recent work under conditions nearer to an acoustic free field have shown that some species at least have this ability (section 1.2). Newer reviews of the subject appear in Hawkins (1973) and Schuijf (1975), the latter including theoretical consideration of phase difference and timing analysis models of the discrimination mechanism in the inner ear.

1.4 SOUND IN THE SEA

Sound may be defined as a periodic motion of the molecules in an elastic medium. Adjacent molecules transmit kinetic energy from an initial disturbance parallel to the direction of propagation of the "sound wave". Variation in pressure, particle velocity, and particle displacement are all manifestations of the passage of sound through a material. The intensity of a sound is usually expressed in pressure units for practical reasons of measurement. In underwater acoustics, sound levels are commonly given in terms of decibels with respect to a reference level of 1dyne/cm^2 = 1μbar, at a standard distance from source of 1m. Use of the air standard of 0.0002bar was discontinued because of the negative values of sound pressure expressed in decibels that result from underwater measurements. Table 1-1 allows comparison of sound pressure values using some of the reference standards that appear in the literature.

The simplest model relating pressure, particle velocity and displacement in a sound wave assumes great distance from the source and small amplitude waves and is known as the

TABLE 1-1 CONVERSION TABLE FOR REFERENCE SOUND LEVELS

dB re dyn/cm	dB re 0.0002 dyn/cm	dB re 1μPa	db re 1μbar	Plane Wave RMS Pressure dyn/cm^2
40	114	140	40	10^2
20	94	120	20	10
0	74	100	0	1
-20	54	80	-20	10^{-1}
-40	34	60	-40	10^{-2}
-60	14	40	-60	10^{-3}
-80	-6	20	-80	10^{-4}
-100	-26	0	-100	10^{-5}

plane wave equation (derived in full in most acoustics textbooks e.g. Camp 1970). For a plane wave of sound the pressure (p) (rms), is related to the particle velocity (u) by:

$$p = \rho c u$$

where: ρ = density of medium

c = propagation velocity of wave.

The term ρc is called the "specific acoustic resistance" or "acoustic impedance" of the medium. For seawater, ρc is about $1.5 \times 10^5 gm/cm^2 sec$ as compared to $42 gm/cm^2 sec$ for air. This is because the speed of sound in the sea is about 4.5 times and the density some 850 times that in air. As a result, an underwater speaker must produce about 60 times the force and 1/60 the diaphragm displacement of a speaker radiating the same energy in air.

The intensity (I) of a sound expresses the rate of energy flow through a given area and is the product of the sound pressure and particle velocity:

$$I = pu = \frac{p^2}{\rho c} = u^2 \rho c$$

The decibel as a unit of intensity is then defined by:

$$L = 10 \log \left(\frac{I}{I_{ref}} \right)$$

where: L = level in decibels

I_{ref} = the reference level of intensity herein $1 dyne/cm^2$ or $1 \mu bar$.

Substitution leads to the working equation for sound pressure level (SPL):

$$SPL = 20\log P_{rms} \text{ db re } 1\mu\text{bar}$$

where: P_{rms} is the measured root-mean-square pressure.

All sound levels in the text correspond to this definition.

Propagation and Transmission Loss:

Sound emanating from a point source diminishes from the effects of spreading, absorption and scattering. "Spreading loss" describes the weakening if the signal due to geometrical effects. Neglecting absorption and scattering, propagation from an omnidirectional source can be viewed as a series of concentric, spherical pressure waves, of equal net energy, radiating outward. Thus, in the absence of reflecting or refracting boundaries, sound pressure diminishes according to the inverse square law:

$$P = 4\pi I r^2$$

where: P = total acoustical power flowing through a sphere of radius r.

For spheres of different radii:

$$P = 4\pi r_1^2 I_1 = 4\pi r_2^2 I_2$$

If r_1 is the reference distance of 1m, then the loss due to spreading (SL) is:

$$SL = 10\log\left(\frac{I_1}{I_2}\right) = 10\log r_2^2 = 20\log r_2$$

Thus, for each doubling of the distance from source, a 6dB loss in sound pressure is observed due to spreading.

Absorption is defined as the transformation of acoustical energy to heat in the medium. This results from the effects of shear viscosity, volume viscosity, and the "ionic absorption" effect of magnesium sulphate and the boron-borate complex (Yeager et al 1973, Urick 1975). Changes in pressure, temperature and salinity affect the absorption coefficient variously, (Urick 1975, Schulkin et al 1962), but for frequencies below 50kHz transmission loss to this effect can be neglected. Similarly, the attenuation in sound pressure due to scattering from thermoclines, haloclines and suspended particulate material is small. A figure of about 0.003dB/km, independent of frequency, has been estimated for the scattering effect in the sea by Mellen et al (1974). For practical purposes, it is usually assumed in underwater sound calculations that intensity diminishes solely due to spreading.

The assumption of a monopole sound source is of course an over-simplification for biological sources as well as underwater sound projectors. These will emit sound waves of a much more complex nature. The plane wave equation applies only to sound waves at a distance (as noted above), or those generated by sources large relative to the wavelength of the frequency produced. Sound close to a small source is propagated in diverging spherical waves. Here, the particle velocity is not in phase with the sound pressure but falls behind by a phase angle that approaches 90° at the source. In this region the particle velocity is not related to the sound pressure by the simple relation for plane waves, but increases disproportionately towards the source. The region of high particle displacement has been termed the "near field" and the region beyond it the "far field" (Harris and van Bergeijk 1962, Harris 1964, and van Bergeijk 1964). While there is no abrupt transition between these zones, fall off of particle displacement is rapid and current practice sets the division at about $r = \lambda/2\pi$. Fig. 1-6 illustrates the near field-far field effect.

Reflection and Refraction at Boundaries:

Sound propogating through a medium reflects from boundaries with contiguous mediums to an extent dependent upon the difference in acoustical impedances and the wavelength of the sound (Urick 1967). A calm sea surface is an almost perfect reflector to normally incident sound and while higher frequencies pass to a small extent through a choppy surface, low frequency sound, having a longer wavelength relative to the wavelength of surface waves is negligibly transmitted. The sea bottom reflects less well, having a higher acoustical impedance than water. Here losses through the interface vary with substrate, ranging from about 14dB in sandy silt to 5dB in rock for normally incident 5kHz sound (Mackenzie 1960).

Reflective or refractive interfaces in the water column such as thermoclines and haloclines, combined with reflection from the surface and bottom, can result in extremely

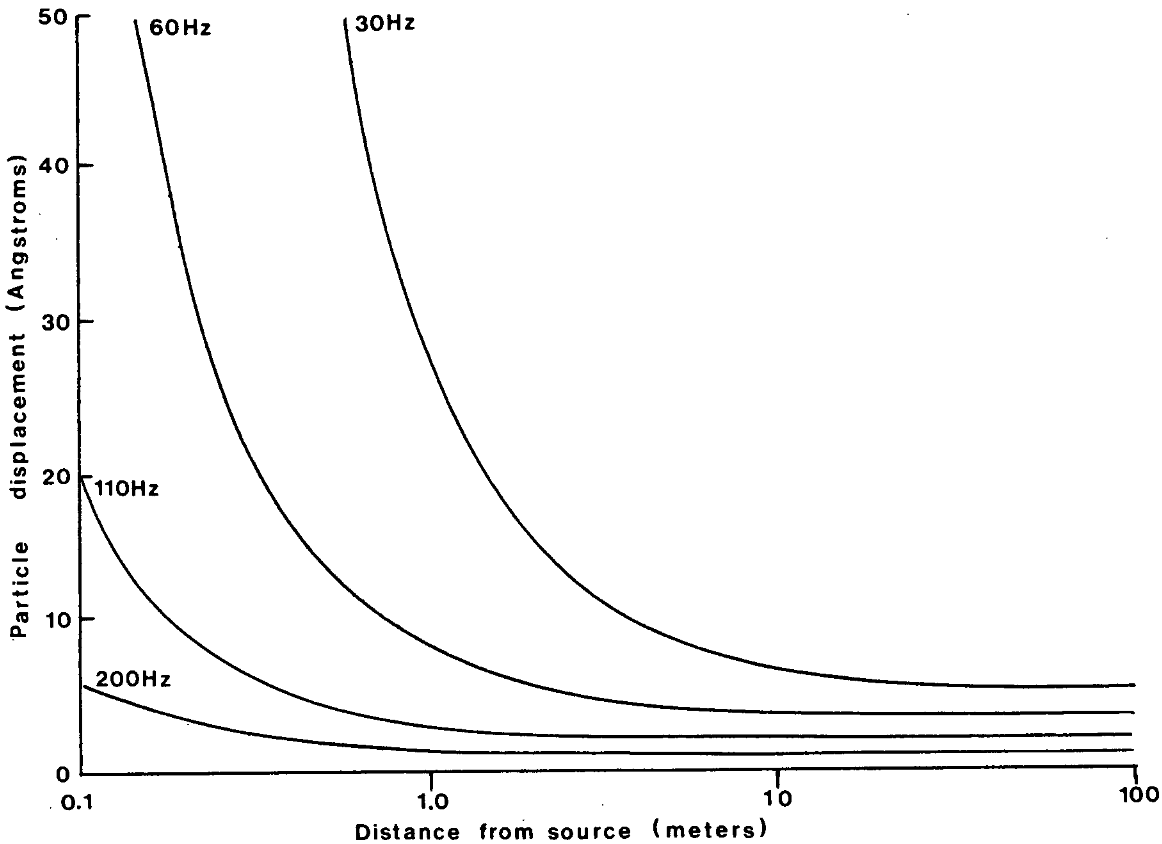

FIGURE 1-6. A plot of particle displacement vs. distance from a monopole sound source illustrates the near-field, far-field effect for several frequencies projected at 1 μ bar re 1 meter (after Hawkins 1973).

complex sound pathways, particularly in shallow water. Simple spherical spreading calculations of transmission loss may provide imprecise estimates of sound intensity at a given distance from the sound source. In addition the signal, if complex may become jumbled as sound waves arriving at a point by different paths get out of phase.

Ambient Noise in the Sea:

Review papers on the sonic environment in the ocean include Loye and Proudfoot (1946), Knudsen et al (1944, 1948), Wenz (1962, 1964) and Piggott (1964). Predominant are sounds from physical sources such as wind and rain, tides and seismic activity. Sounds of biological origin may transiently be ascendant (Dobrin 1947; Fish 1964; York 1972), particularly in shallow water. Probably the most widespread and persistent biological sound is a "crackling" or "frying" that has often been traced to snapping shrimp (Alpheidae) and also to barnacles (Cirripedia), mussels (Mytilidae), sea urchins (Echinidae) and other invertebrates. Reviews of sound production in fish include Tavolga (1960, 1964, 1971), Moulton (1963), Fish (1964), Winn (1964), and Fish and Mowbray (1970). A composite illustration of ambient noise spectra from Wenz (1962), appears in Fig. 1-7.

1.5 OBJECTIVES OF THE STUDY

The study was initiated to satisfy the curiosity that the author, himself a troller, had developed regarding the role of sound in the B.C. troll fishery. Numerous dockside stories

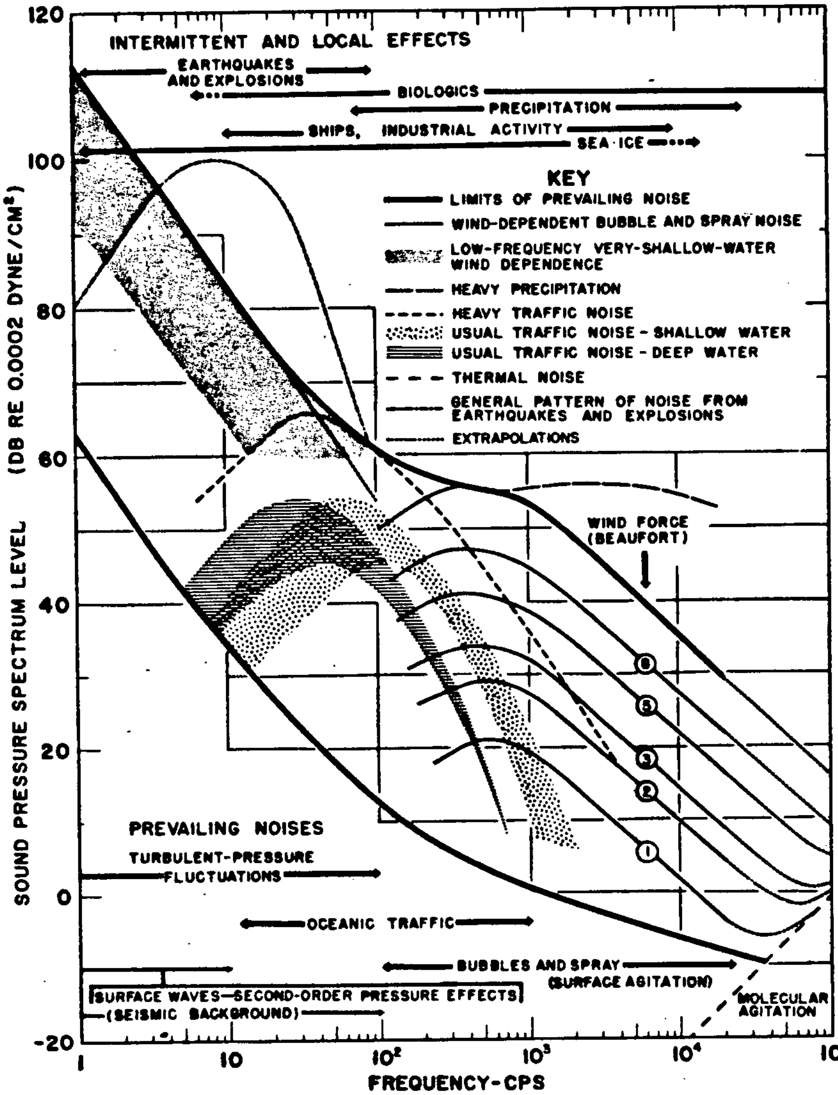

FIGURE 1-7. A composite illustration of oceanic ambient noise showing sound spectra from various sources (after Wenz 1962). Sound pressure units may be converted to dB re 1 μ bar by adding 74 dB.

of dramatic catch increases attributed to changes in a vessels drive train or steering gear lead to this attempt at systematic investigation of the phenomena. The main point at issue is whether vessels with good sound profiles actively attract fish or just do not repel fish by non-emission of repulsive sounds.

2.0 THEORY FORMATION AND EXPERIMENTAL DESIGN

2.1 THEORY FORMATION

PROPOSITIONS

Catch rates vary widely between vessels in the British Columbia troll salmon fishery. Fishermen attribute at least part of the variance to the sound output of the vessel (Boyes pers. obs.).

ASSUMPTIONS

Pacific salmon utilize sound in addition to their other senses in the location of prey and avoidance of predators.

INFERENCES

Projection of characteristic prey or predator sounds at a high level from within the gear array of a salmon troller will either attract salmon and stimulate feeding, or repel the fish and suppress feeding activity. The catch rate of the vessel, compared to a control condition, will improve or decrease as a result of the sound projection.

2.2 EXPERIMENTAL DESIGN

An obvious starting point for the study was the sounds of the boats and the fish themselves. Analysis and comparison of these sound spectra might show similarities responsible for attraction or stimulation of feeding in salmon. Similarly, comparison of boat spectrums with those of salmon predators could reveal the source of a negative effect on catch rate. The study was directed towards the attraction alternative based on the success recorded with a number of fish species in the literature (reviewed in section 1.2). That the author makes his living catching salmon rather than chasing them away was not an inconsiderable part of this decision.

The second stage of the investigation consisted of recording the sounds made by various salmonids actively taking pelleted feed, then projecting these sounds back to the fish. Success in eliciting feeding or searching behavior in a number of species has been reported (see section 1.2) with this procedure, although negative results have been common also. A positive result of some kind would establish that the sound equipment was performing adequately in level of output and fidelity of reproduction.

At sea playback of salmonid feeding sounds and simulated feeding sounds in an effort to increase the catch rate of a commercial troller comprised the third stage of the study. The catch rate of trollers characteristically exhibits wide variation through the day with maxima often associated with periods of slack tide and/or low light at daybreak and dusk. Thus, for much of the day gear is being presented to the fish with no response. They are, in the vernacular, "off the bite". The experiment was structured and performed to minimize the effects of this natural variation on the results. Trials were only conducted during slow periods of the day so that test sounds were presented to minimally excited fish. It was expected that if these sounds had a stimulative or attractive character to the fish, the effects on catch rate would be larger than with fish already biting well and thus more visible. With fewer fish per line the time required to pull the gear and reset it is also reduced, giving a lower pulling time/soaking time ratio and delineating more clearly the test and control periods. In addition, low catch rates mean fewer hooks are occupied during a trial leaving more available to new fish. Saturation of the gear (commonly 7-10 hooks/side) is thus avoided.

3.0 METHODS AND MATERIALS

3.1 RECORDING, PLAYBACK AND ANALYTICAL EQUIPMENT

Underwater recordings were made with a Sparton 60CX123 hydrophone onto a JVC K13-1636 MKII cassette tape recorder. Playback was from the same recorder, through an Aquavox UW 60 underwater loudspeaker with a built-in 100volt line transformer, driven by a Sonic Barrier public address amplifier (100volt output). Sonograms were made on a Kay 7029A spectrum analyzer. Specifications and calibration data for recording and playback equipment follow.

HYDROPHONE:

MODEL:	Sparton 60CX123
COMPOSITION:	Lead-Zinconate, Piezo Electric with integral preamplifier
RECEIVING RESPONSE (dB/volt/μbar):	49± 3dB Flat 0.04-5.0 kHz (see Fig. 3-1)
POWER REQUIREMENTS:	8.7v ± 5% @ 500 A Low noise power supply shown in Fig. 3-2.

TAPE RECORDER:

MODEL:	MODEL JVC K13-1636 MKII
FREQUENCY RESPONSE:	25-17,000Hz (30-15,000± 3dB
SIGNAL/NOISE:	57dB
WOW & FLUTTER:	0.08% (WRMS)
CROSSTALK:	65dB (1kHz)
INPUT SENSITIVITY/IMPEDANCE:	0.14mV, 20-10k OHMS
OUTPUT LEVEL/IMPEDANCE: . . .	50mV, 2.5k OHMS
POWER CONSUMPTION:	9watts

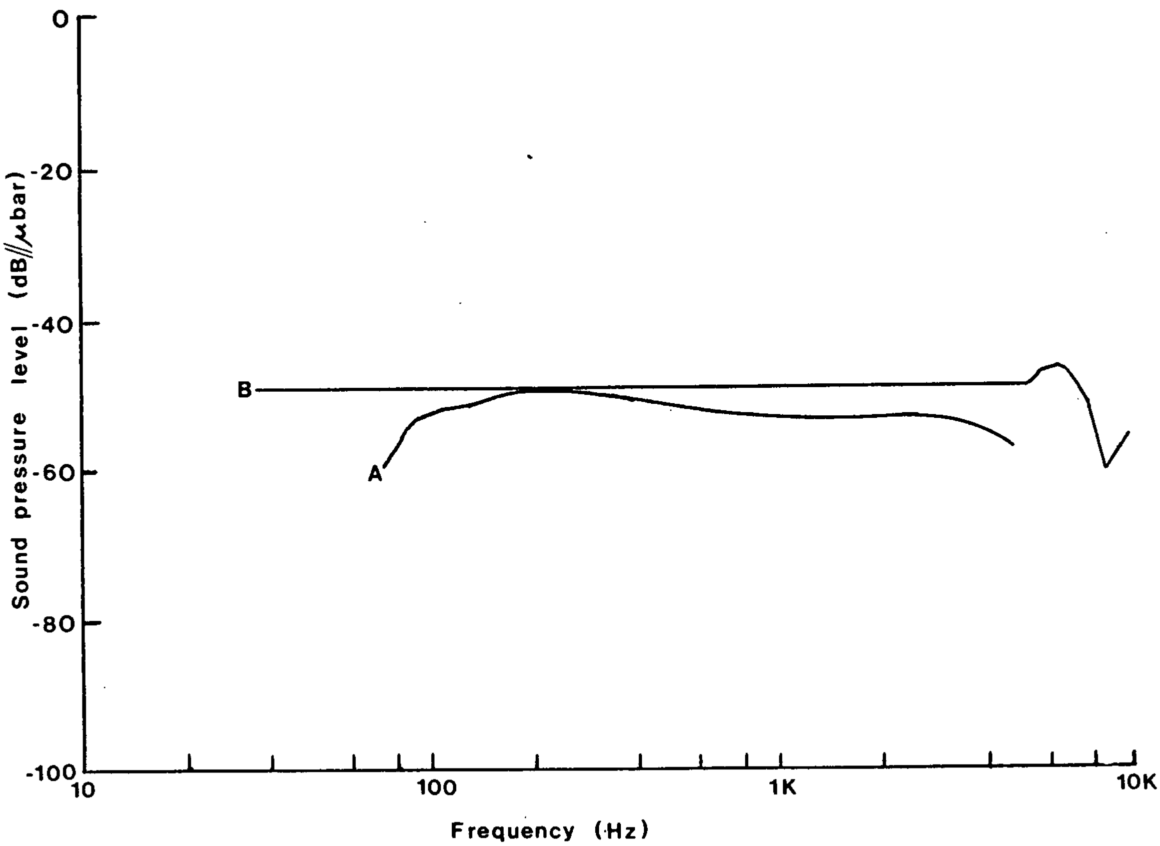

FIGURE 3-1. A/ Measured sensitivity of a Sparton 60 CX 123 hydrophone and preamplifier at a depth of 30m. B/ Manufacturers curve of frequency response for the Sparton 60 CX 123 hydrophone and preamplifier.

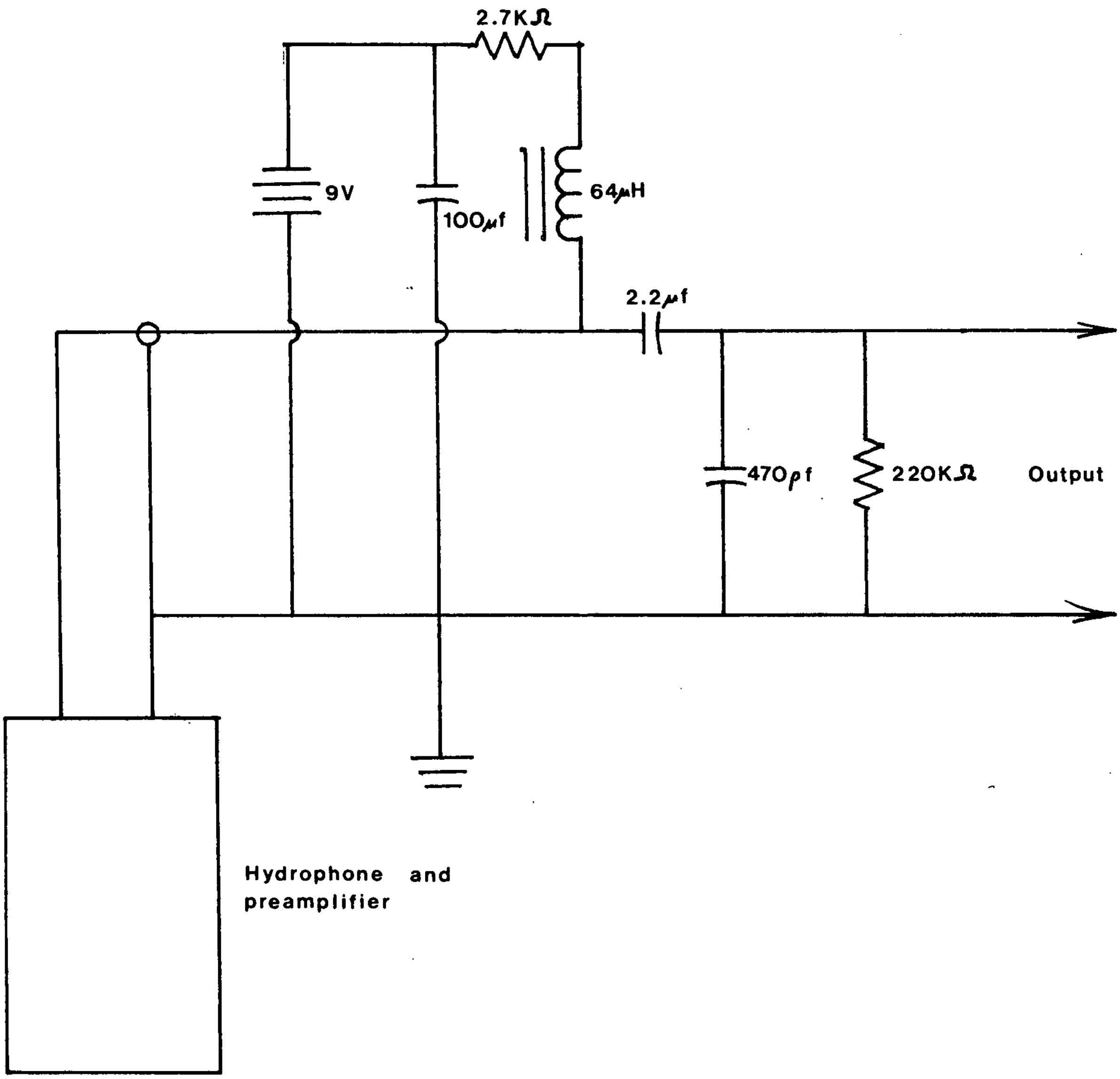

FIGURE 3-2. The noise reduction circuit of the hydrophone power supply.

SOUND PROJECTOR:

MODEL:	Aquavox UW60
MAXIMUM POWER INPUT:	50watts RMS
FREQUENCY RESPONSE:	100Hz - 50kHz (See Fig. 3-3)
MAGNETIC SYSTEM:	Permanent Magnet
MAXIMUM OPERATING DEPTH: . .	50m

AMPLIFIER:

MODEL:	Sonic Barrier
POWER INPUT:	12V D.C.
INPUT IMPEDANCE:	200 OHMS - 50k OHMS
INPUT LEVEL (MIC):	3mV
OUTPUT IMPEDANCE (100v line):	16 OHMS

SOUND GENERATOR:

MODEL:	Custom, using T.I. SN76477N Complex sound generator I.C.
POWER SUPPLY:	9V D.C.
LOW PASS FILTER:	Rolloff at 800Hz Circuit shown in Fig. 3-4

3.2 RECORDINGS OF TROLLERS

Fishboats were recorded from the end of a dock with the hydrophone suspended two meters below the surface. Boats ran by about 4meters from the hydrophone and were recorded at three speeds; a "slow troll" (a slow salmon trolling speed, about 1.5m/s), "fast troll" (2m/s), and "tuna speed" (approx. trolling speed for tuna, 4-5m/s). Skippers were instructed to select these speeds using their own judgement and experience with their boats.

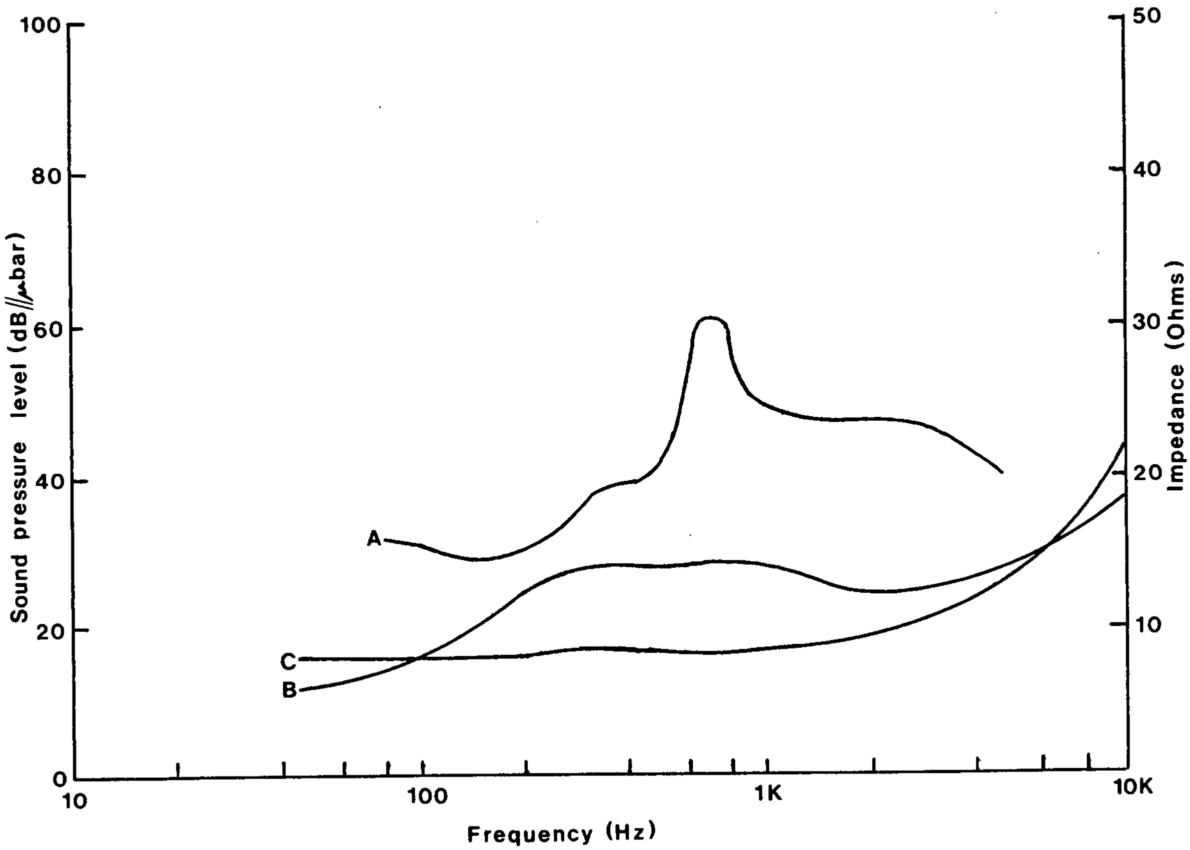

FIGURE 3-3. A/ Measured output of Aquavox UX60 loudspeaker used in playback driven at 1 amp., RMS at a depth of 40m in an acoustical free field. B/ Measured output of an Aquavox UW60 driven at a constant current of 1 amp. in the AMTE acoustic tank, England (manufacturers data). C/ Measured impendance of the UW60 at 1 amp in the AMTE acoustic tank (manufacturers data).

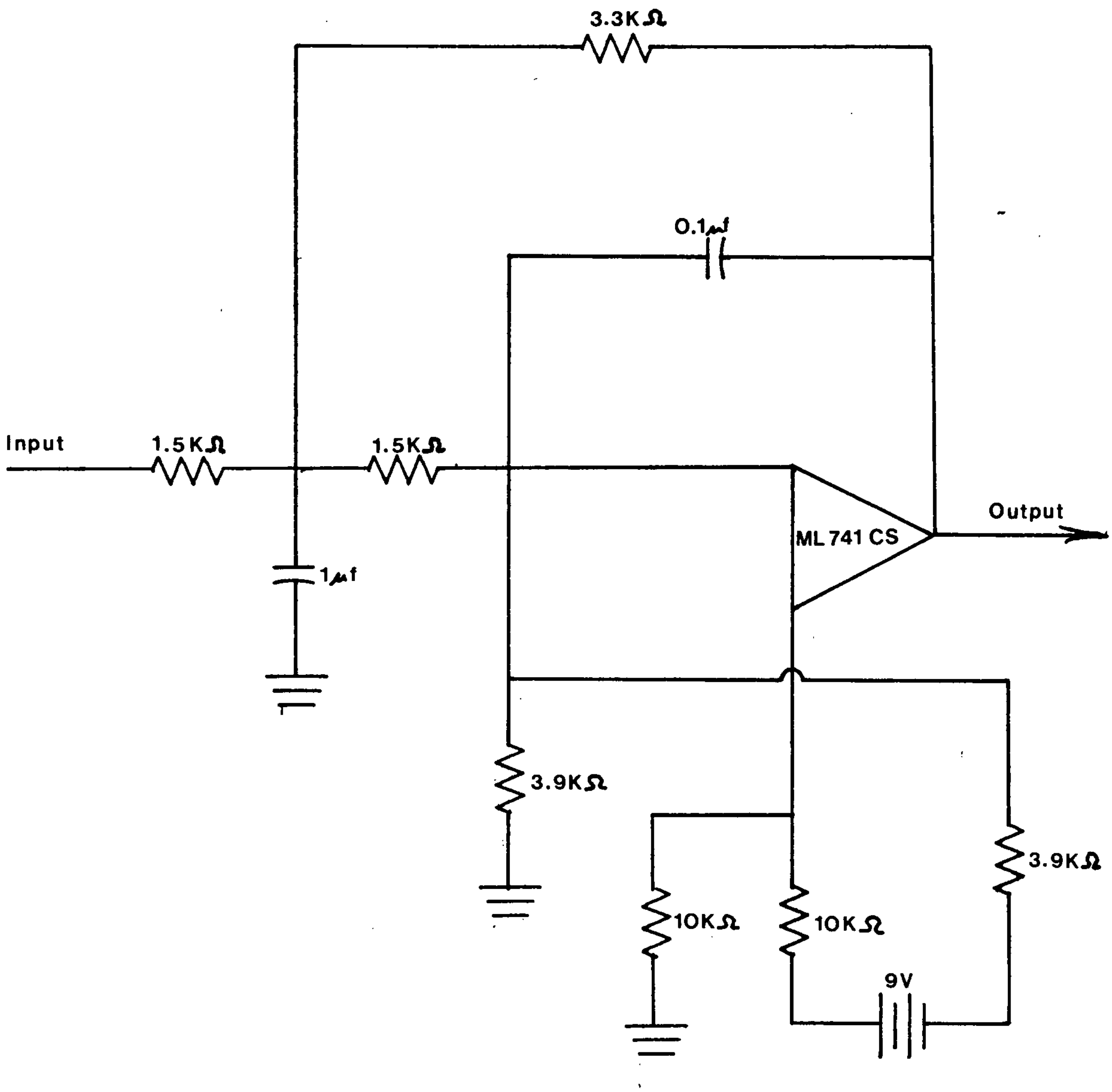

FIGURE 3-4. Low pass filter used with complex sound generator to produce Test Tape II.

3.3 RECORDINGS OF FISH

Herring were recorded in "wild" schools and captive in net pens. Wild schools were located by echo sounder while in shallow water during spawning season on the west coast of Vancouver Island or in the Gulf of Georgia (March 1980). The hydrophone was lowered to the depth of the school and recordings made. Captive herring were recorded at the Pacific Biological Station in Nanaimo. Here the hydrophone was placed within the net pen.

Coho and chinook salmon (1-2.5kg), as well as larger rainbow trout (2-3kg) were recorded in net pens at the Pacific Biological Station. The hydrophone was placed within the enclosure. Pelleted feed was thrown into the pens to initiate feeding motions such as accelerations, fast swimming and rapid turns.

3.4 PLAYBACK IN PENS

The sound projector was placed inside or just outside the net enclosure and test sounds played to herring, coho, chinook, and rainbow trout. Reactions of the fish to test sounds were observed from the catwalk around the pens.

3.5 PLAYBACK AT SEA

For the sea trials, the projector was towed behind the troll vessel within the gear array, Fig. 3-5 at a depth of 7-8meters. The two main lines were pulled every 1/2hour, the

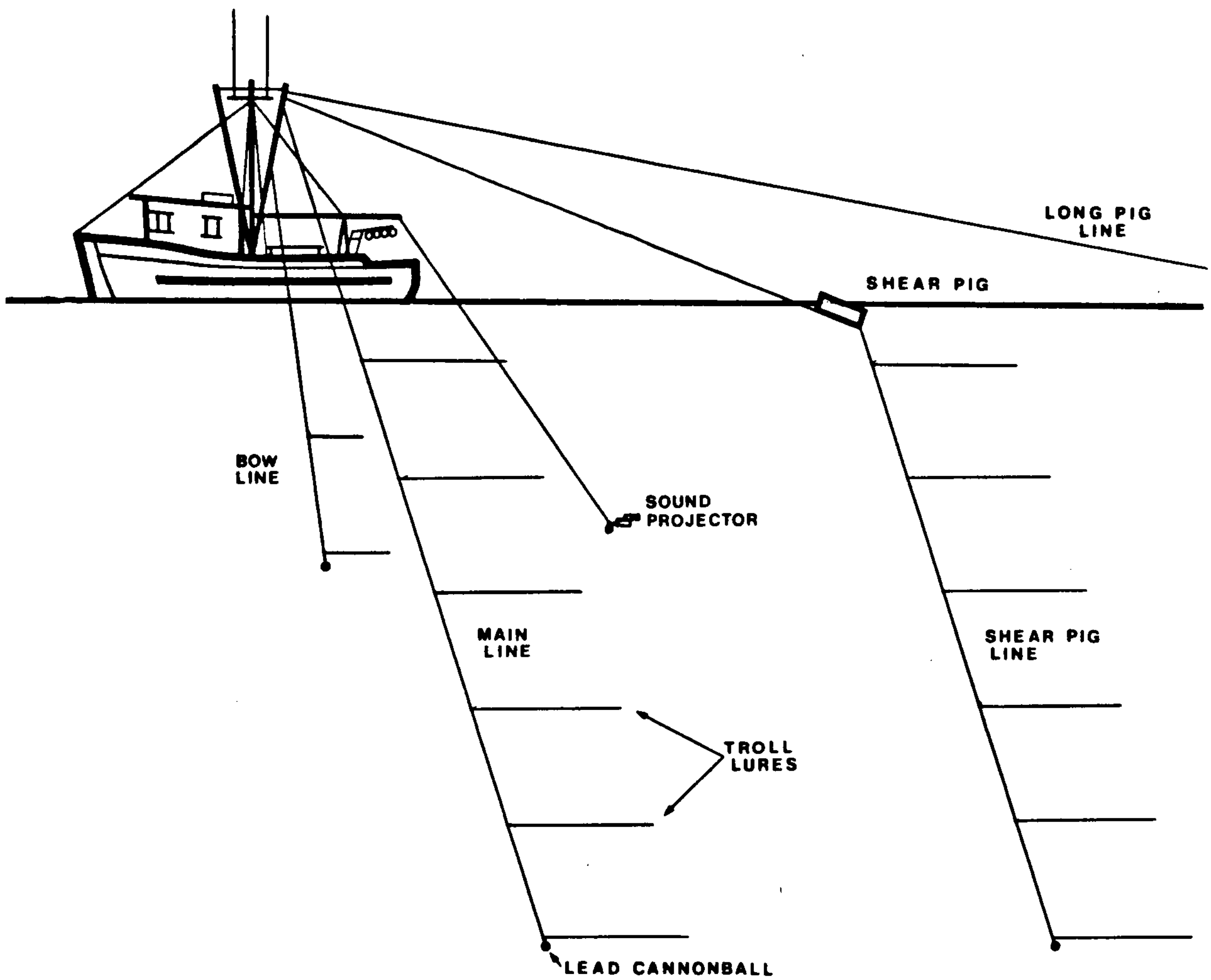

FIGURE 3-5. The position of the sound projector within the gear array during test and control periods.

numbers and species of fish captured recorded, and the lines reset. This generally took about 4-5mins. The test sounds were cycled on and off every 1/2hour with the switch occurring just after the lines had been reset. Three separate sounds were used in the trials, denoted test tapes I, II and III, shown in the sonograms of Figures 3-6, 3-7 and 3-8. The lures fished included flashers and hootchies, spoons, plugs and butterflies, arranged in a pattern appropriate to the species selectivity of the individual types of lures and to the vertical species distribution of the salmon in the area. No changes to gear were made during the trial periods save replacing worn or lost pieces.

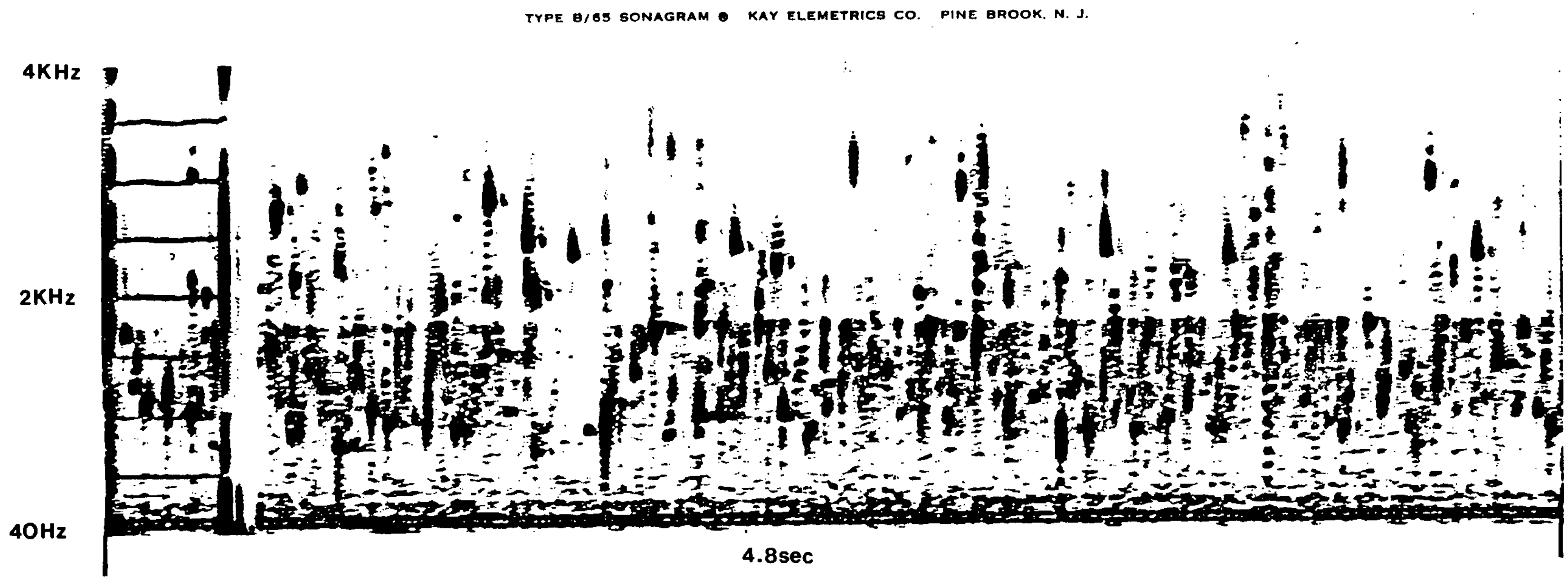

FIGURE 3-6. Sonogram of Test Tape I; a recording of trickling water. Filter bandwidth 22.5 Hz.

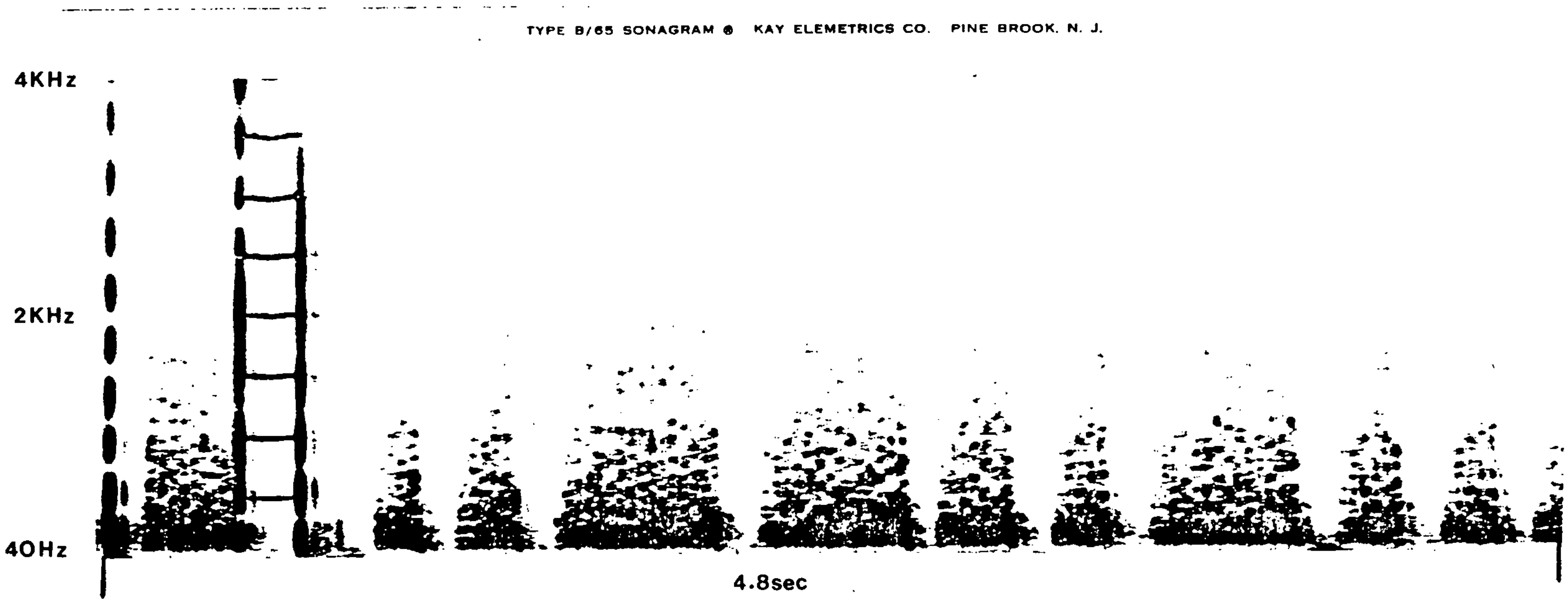

FIGURE 3-7. Sonogram of Test Tape II; irregular pulsed output of a noise generator cycling at 28 Hz. Filter bandwith 22.5 Hz.

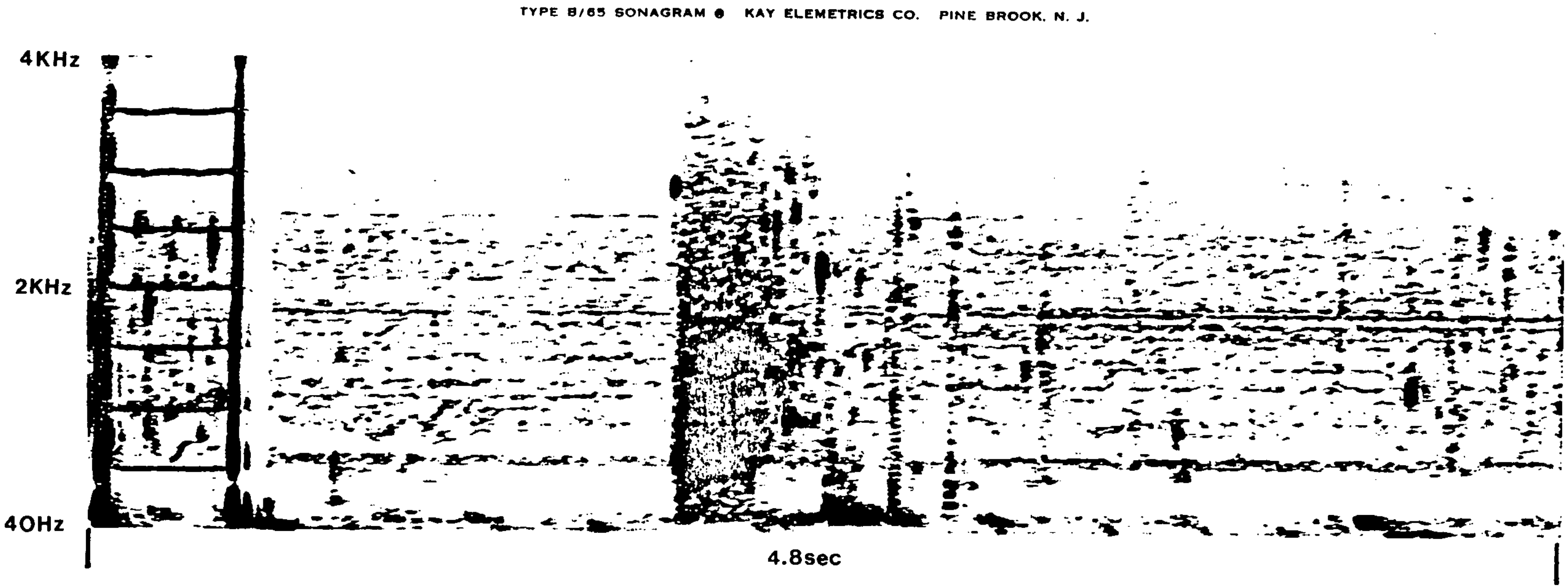

FIGURE 3-8. Sonogram of Test Tape III; feeding sounds of rainbow trout (2.5-3Kg). Filter bandwidth 22.5 Hz.

4.0 RESULTS AND DISCUSSION

4.1 RECORDINGS OF TROLLERS

Recordings were made of ten trollers from 9.7-14.5m in length. Eight were of traditional carvel plank construction and two were single skin fiberglass. Wide variation in acoustic output was apparent between boats and at different speeds. Figures 4-1, 4-2 and 4-3 are sonograms of a 10m wooden troller at a slow troll, fast troll and at tuna speed. Frequency is on the y axis, time on the x, with intensity a function of the darkness of the trace. The two jagged traces at the top of each sonogram are instantaneous sections of the recording. For these the frequency scale is reversed and intensity is proportional to the height of the trace.

Figure 4-2 shows the characteristic broadband (here 1-6KHz) traces associated with cavitation of the propeller (Ross 1976). This may be due to one or more bent blades, an unbalanced wheel, or a bent tailshaft (Erickson 1979). Trollers guard against cavitation noise which may be heard in the stern of the vessel by putting one's ear to the hull, as it is believed to affect catch rate. A considerable increase in both intensity and the upper frequency limit of the sonogram is evident at tuna speed, Figure 4-3. Here the vessel is encountering wave-making resistance so that in addition to the engine, reduction gear, shaft and propeller turning considerably faster surface water noises are appearing also. The operation of auxiliary equipment, hydraulics, pumps, motors, etc. was often noticeable when cycled on and off. Figure 4-4 shows a

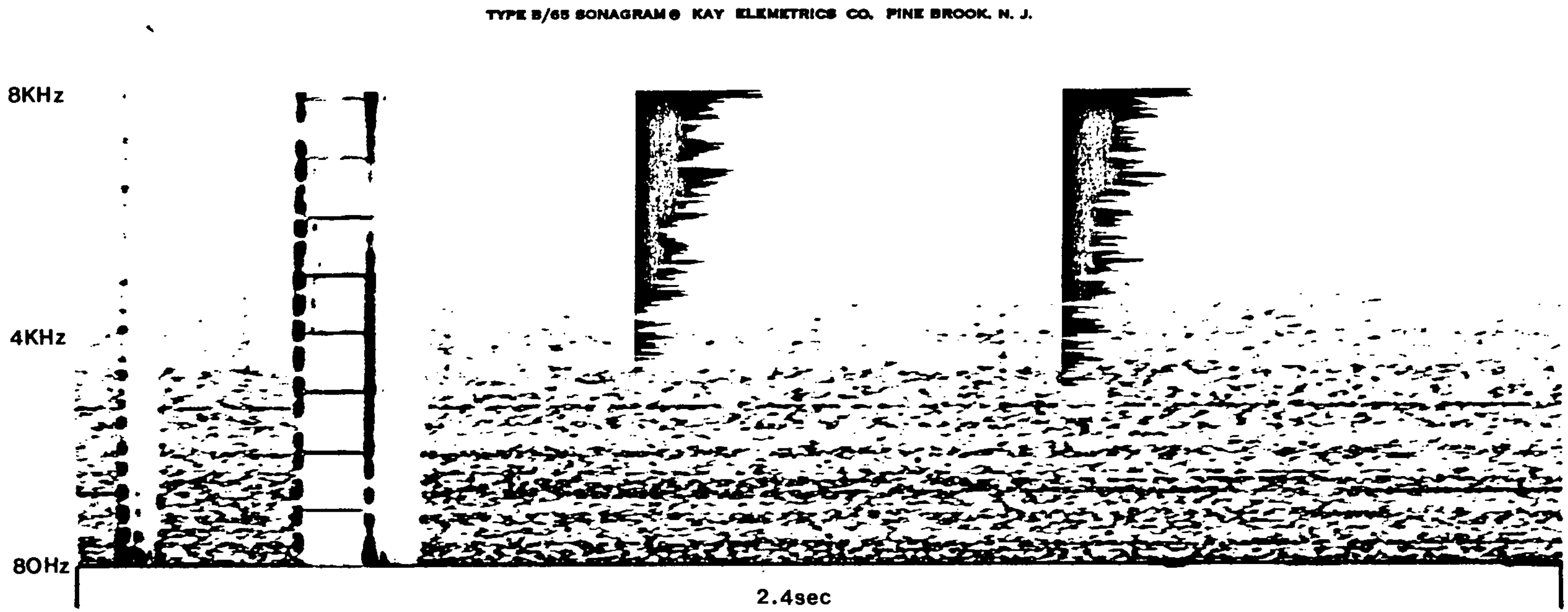

FIGURE 4-1. Sonogram of 10m wooden troller at a slow trolling speed (1.5m/s). Filter bandwidth 45 Hz.

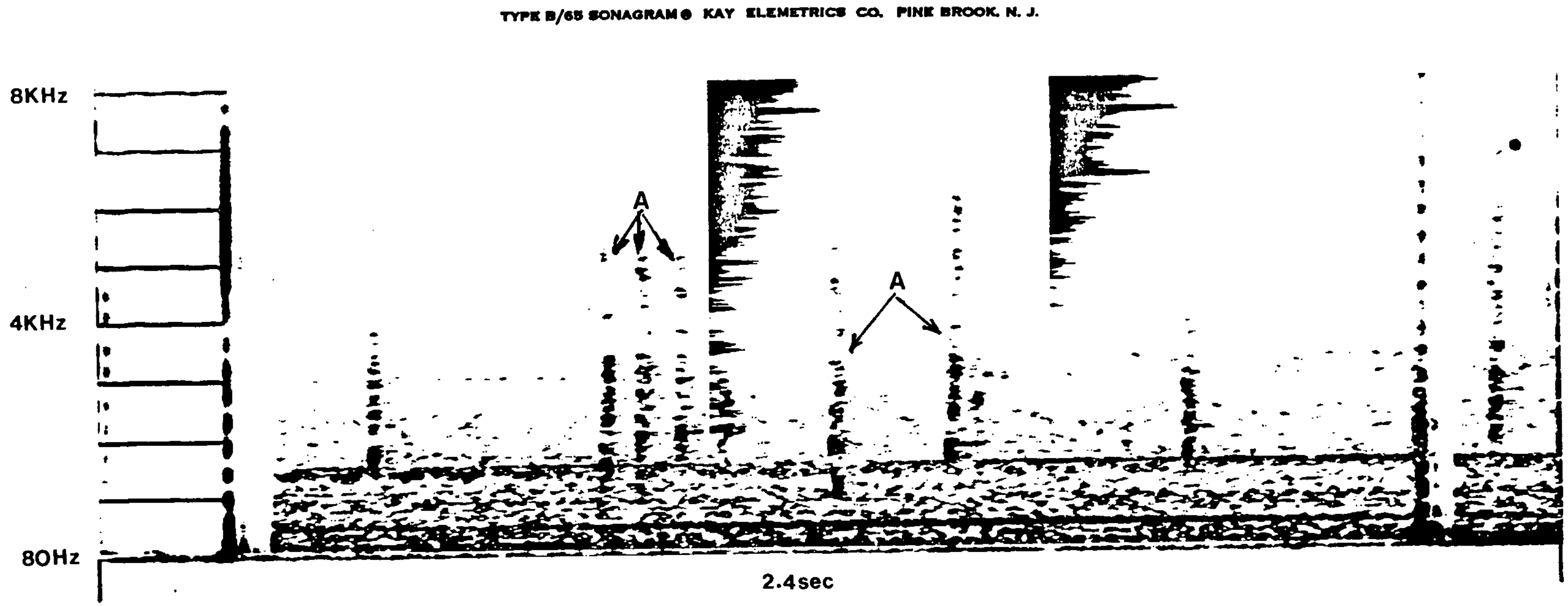

FIGURE 4-2. Sonogram of a 10m wooden troller at a fast trolling speed (2m/s). A/ Indicates traces associated with cavitation of the propeller. Filter bandwidth 45 Hz.

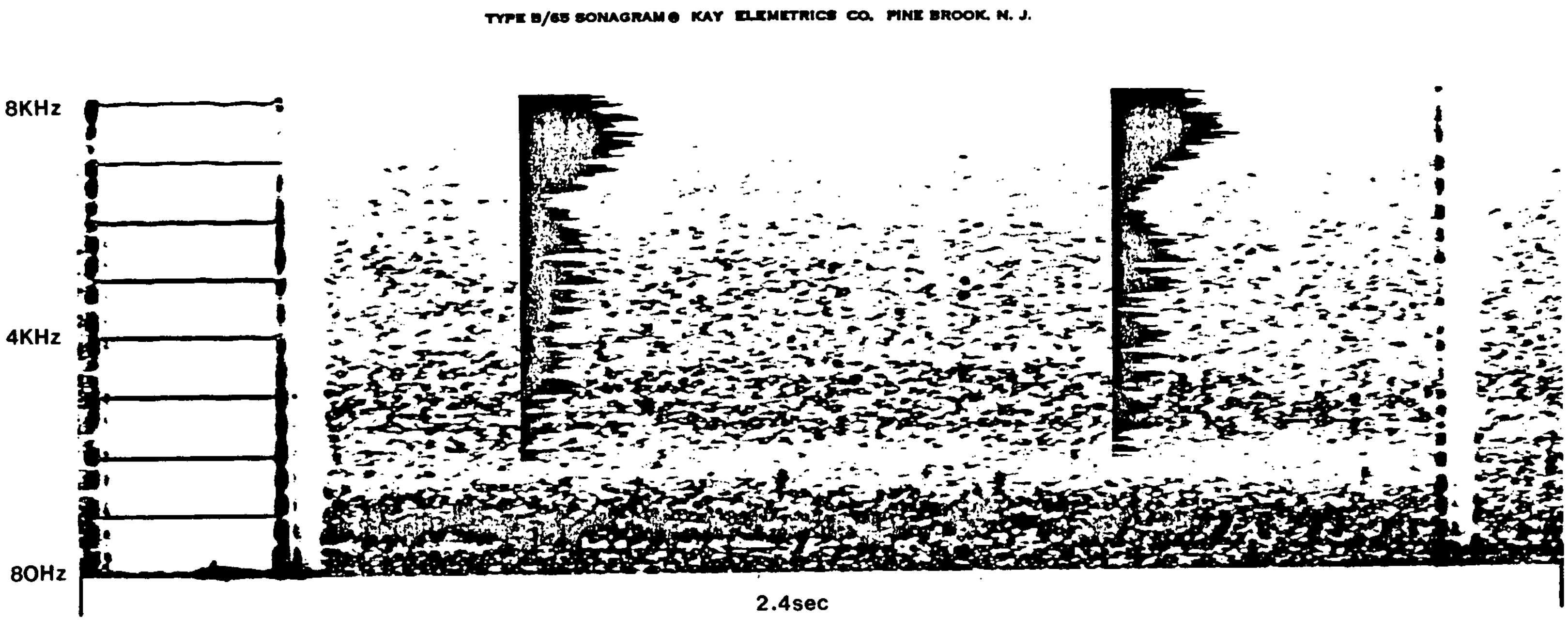

FIGURE 4-3. Sonogram of a 10m wooden troller at tuna speed (4-5 m/s). Filter bandwidth 45 Hz.

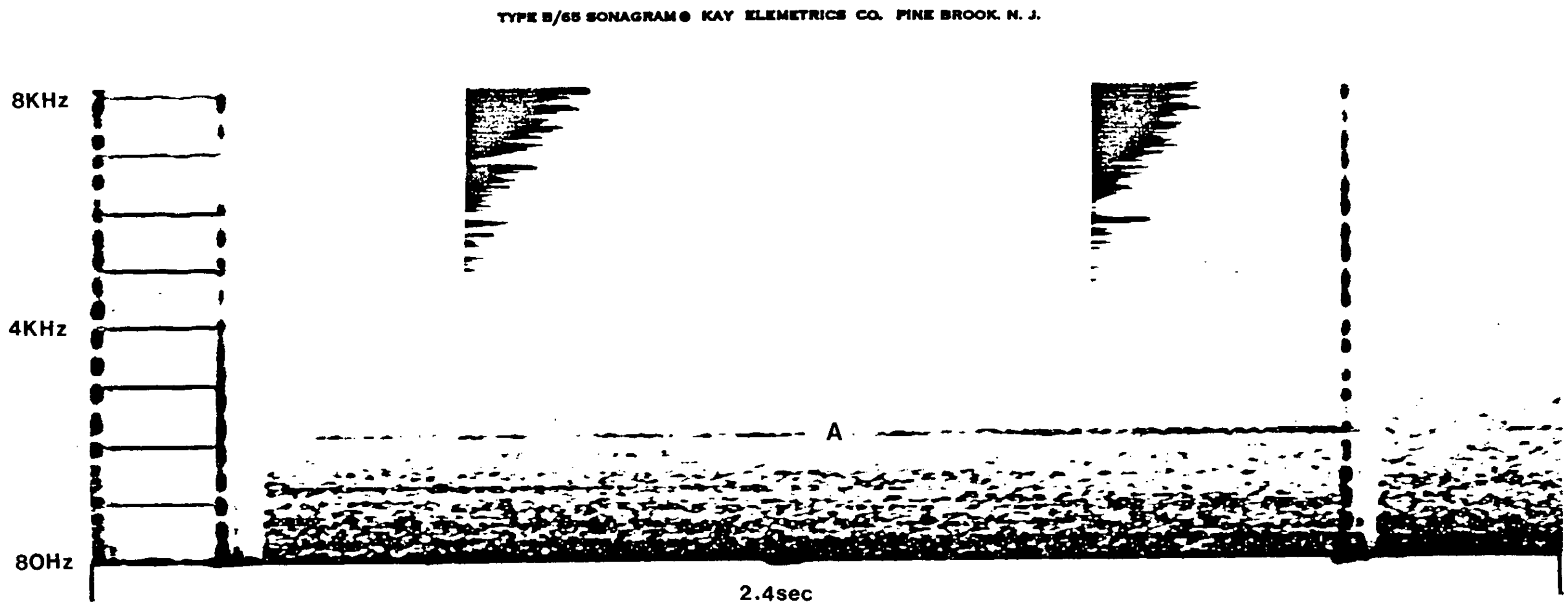

FIGURE 4-4. Sonogram of a 14.5m wooden troller at a slow troll with hydraulically driven refrigeration compressor operating (A). Filter bandwith 45 Hz.

trace at about 2.2KHz caused by a variable speed hydraulic pump driving a refrigeration compressor.

A slow-troll sonogram of the author's vessel, used in the sea trials is shown in Figure 4-5. Propeller noises are reduced in this recording as the hydrophone was close to the boat (1.5m) and abeam the vessel. Engine noises are predominant, showing narrow bandwidth traces associated with particular engine components at about 600RPM. The output level of the test vessel with main and auxiliary engines running was 20dB re 1μbar at 1m while stationary. This is appreciably higher than the level measured by Erickson (1979) with albacore jig boats (about 10dB reμl bar). Gear, shaft and propeller sounds would likely not add to this appreciably at trolling speed as engine noises tend to predominate. The thresholds reported for pink and Atlantic salmon, and some other non-ostariophysine species (Figures 1-4, 1-5) indicate that salmon can acoustically detect troll vessels in the frequency range 20-400Hz. In the most sensitive region the range of detection will approach 30m. It is noteworthy that if Erickson's (1979) output levels are valid, the maximum detection distance is only 1m.

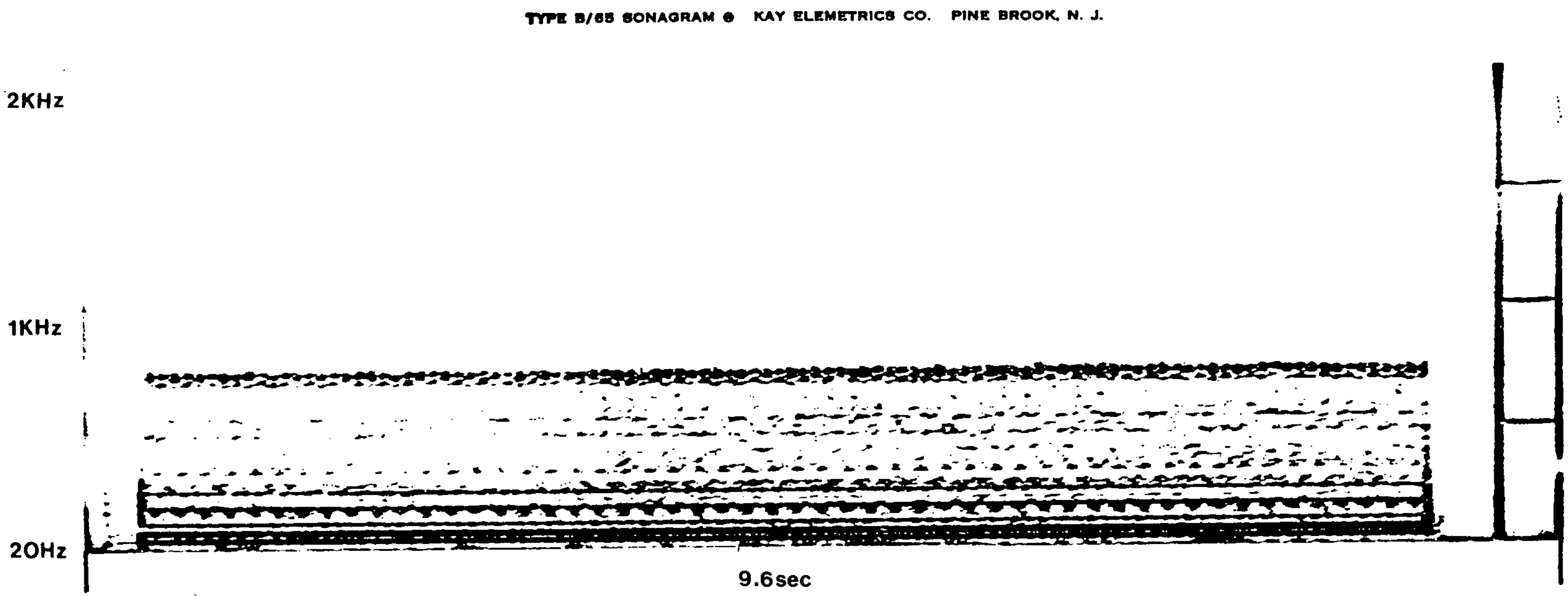

FIGURE 4-5. Sonogram of the author's vessel (13.1m), used in the sea trials, at a slow trolling speed (1.0-1.5m/s). Filter bandwidth 11.25 Hz.

4.2 RECORDINGS OF FISH

Obtaining quality recordings of herring while schooled in shallow, calm water proved difficult due to the ubiquitous herring fleet and the considerable background noise resulting. Fish were located by echo sounding and the boat either anchored on the school or allowed to drift with machinery shut down. These pre-spawning fish proved to be fairly quiet with the only sound apparent being high pitched "crackling" or "frying" sounds centered on 4KHz. These may be produced by branchiate or skeletal movements of the herring, although this type of sound is also made by certain barnacles (Cirripedia), mussels (Mytilidae), and urchins (Echinidae)(Fish 1964).

Recordings of captive herring (several thousand) in the net pens at PBS were of better quality with lower background noise levels. Direct observation of the fish during recording also allowed sound-activity correlations. The fish tended to circle within the net, sometimes piling up in one corner which occasioned surface thrashing and rapid swimming until the school reversed its direction. The above mentioned frying sounds found in recordings of wild fish were presented at all times near the school. A sonogram showing the patterns and bandwidth of these sounds is shown in Fig.4-6. They range 3.5-5KHz. During crowding and accompanying rapid swimming, sounds dubbed "knocks" were very evident. These are shown in Fig.4-7. The frying sounds of Fig.4-6 appear periodically in this sonogram as well. Some of the low frequency (<500Hz) pulses are due to fish hitting the hydrophone and cord and causing feedback.

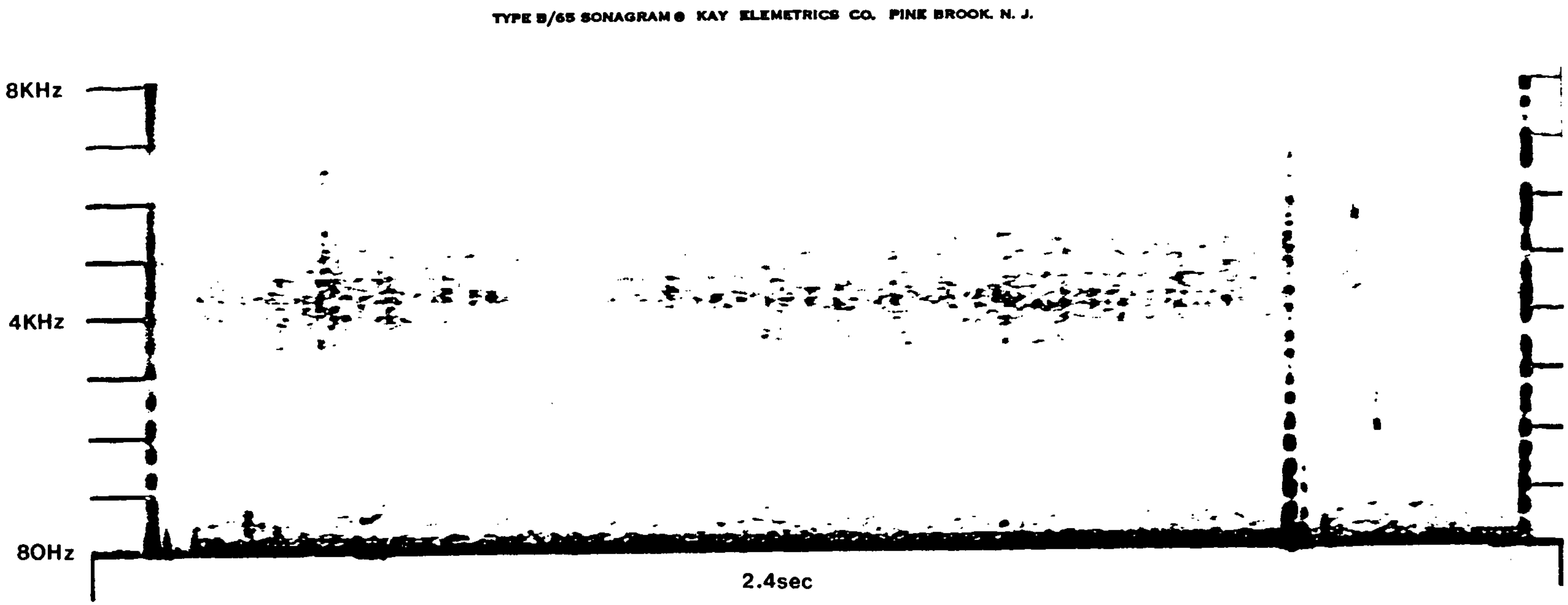

FIGURE 4-6. Sonogram of herring "scratches". The recording was of captive herring in a net pen at the Pacific Biological Station. Filter bandwidth 45 Hz.

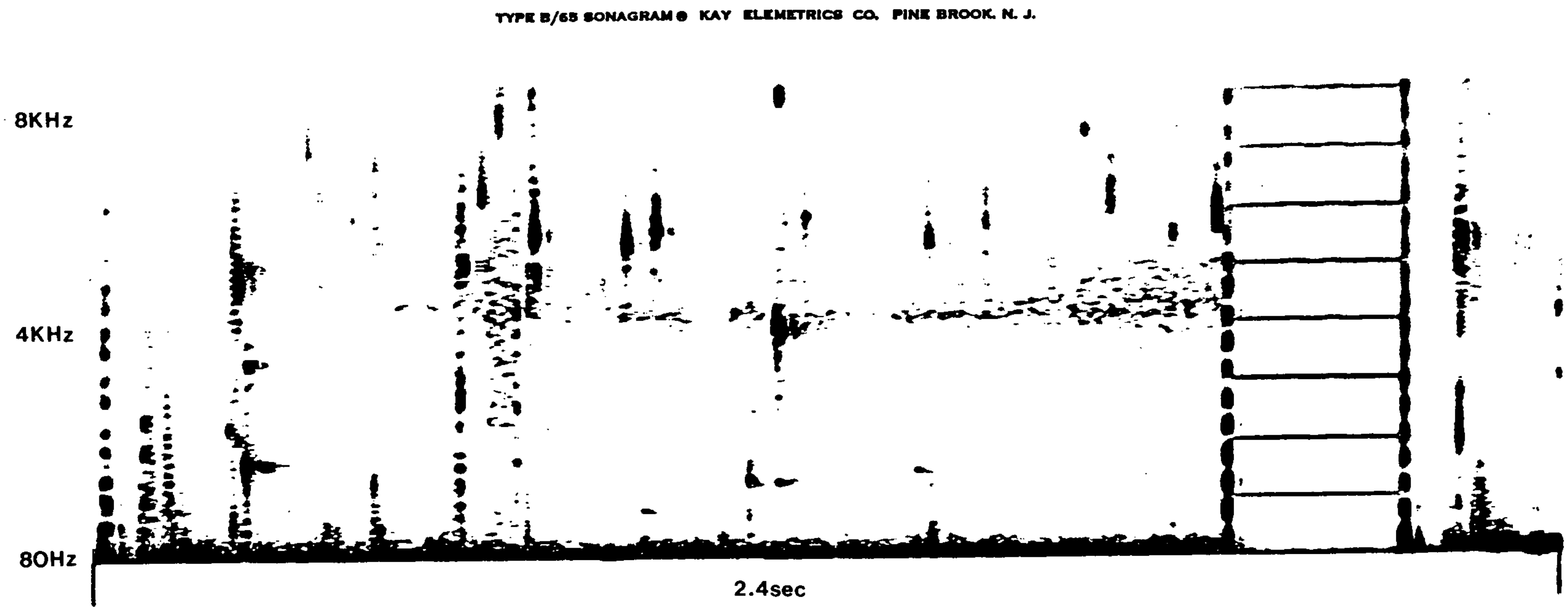

FIGURE 4-7. Sonogram of herring "knocks", produced by active fish in a net pen at the Pacific Biological Station. Filter bandwidth 45 Hz.

A sonogram of juvenile coho (500gm) feeding actively on pellets is shown in Fig.4-8. These fish were swimming quickly with rapid turns and accelerations as they competed for the food. The fish did not break the surface during this recording, thus these knocking sounds were plainly generated underwater. Similar sounds occurred in recordings of juvenile chinook (500gm), adult coho (1.5-2.5kg) and adult rainbow trout (2.5-3kg). Frying sounds were absent from recordings of captive salmonids but considerable shipping noise is evident in the background of Fig.4-8.

4.3 PLAYBACK IN PENS

As detailed in section 1.2, positive responses to playback of feeding sounds have been obtained with a number of species (Moulton 1960, Hashimoto and Maniwa 1966, Maniwa 1975). Attempts to elicit similar responses with coho and chinook salmon and rainbow trout failed. The subject fish were enclosed in net pens at PBS and lived on a pelleted diet. Playback of the sounds of pellets being thrown into the pens and of the fish feeding on them was made to unsatiated fish at output levels as high as 55dB re 1μbar at 1m. Figs.3-8 and 4-8 are sonograms of such sounds. The sound projector was suspended within the pen, not more than 2m from the fish. No response of any kind was observed. Attempts to produce a startle effect with pure tone and oscillating tones also failed.

It may be that these fish, hand fed and held in an area with a very high background noise level, have become conditioned to visual cues only. Pellets thrown into the pens

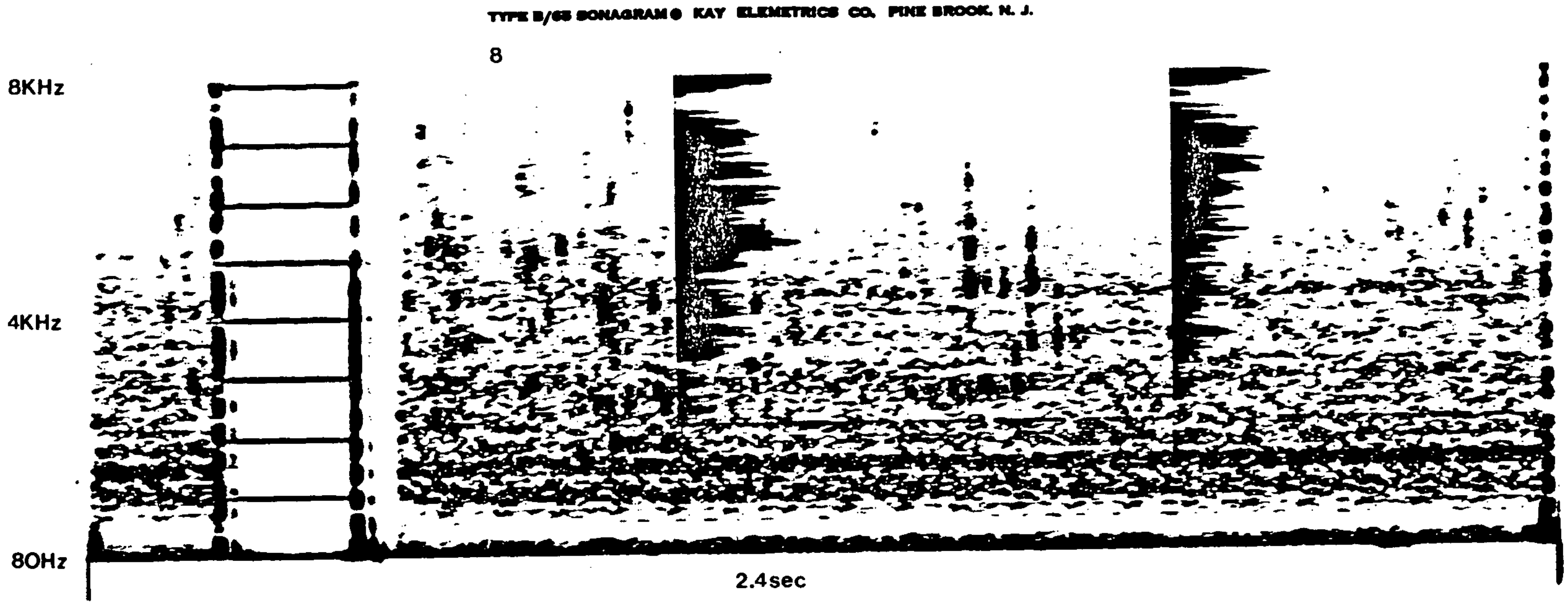

FIGURE 4-8. Sonogram of juvenile coho salmon actively feeding on pellets. The intense broadband traces are the fish noises (indicated) considerable shipping noise is evident in background. Filter bandwidth 45 Hz.

make a significant disturbance on the surface. The fish are also sheltered from predation within their nets and thus lack another powerful stimulus to use of their auditory sense. These considerations may explain the observed lack of reaction to sounds.

4.4 PLAYBACK AT SEA

Attempts to attract salmon at sea to a sound source were carried out during August and September of 1981 and 1982 off the southern west coast of Vancouver Island. The number of trials was constrained by the fishing patterns of the vessel and by weather. Tests were practical only when the number of fish caught per day was less than about 50 due to the time required to pull the gear, remove fish, and reset as well as processing time (the fish must be stunned, bled, dressed, washed, frozen, glazed and stowed). Two people were required to conduct trials so that gear could be checked and reset in accordance with the schedule. Often only a few cycles were possible before the crew was called to other duties. Moderate weather with good visibility was required to tow the sound projector without risk in the large fleets of boats that prevailed in the area. Strong tidal action caused a number of tangles between the speaker and trolling lines requiring abortion of the trial in progress.

The three types of sounds used in the trials (Figs.3-6, 3-7, 3-8), were chosen based on sounds reported to be successful in the literature, and for resemblance to recorded sounds of herring and salmonids.

Test Tape I was a recording of trickling water (Fig.3-6). The broadband pulses evident in all the recordings of active fish were well mimicked by this method, and a very low noise tape could be made. The erratic pulsed timing of the sound, roughly 20Hz, accorded well with successful sounds in the literature (Steinberg *et al* 1965, Richard 1968).

Test Tape II is the recorded output of a custom made sound generator utilizing a Texas Instrument SN76477N complex sound generator integrated circuit (Fig.3-7). The noise function of the chip was modified with a low-pass filter (Fig.3-4) to roll off at about 800Hz, then cycled at about 28Hz. This sound was then pulsed irregularly. Again, this sound was designed to resemble observed fish sounds and those in the literature. It differed from Tape I in it's greater emphasis on low frequency.

Test Tape III (Fig.3-8) consisted of repeated rainbow trout feeding sounds. This tape was used at the end of the sea trials after it became apparent that the synthesized sounds were ineffective.

The results of the playback at sea are shown in Tables 4-1, 4-2 and 4-3. With Tape I, 31 fish were caught with the sound on, and 31 with it off. Tape II gave a result of 17 and 24 respectively, While Tape III yielded 7 and 8. A slight negative correlation is evident with Tape II but a paired t-test on the data indicated that the result was not significant at $\alpha=.05$.

TABLE 4-1: Salmon Catch During Cycled Playback of Test Tape I; Water Noises

DATE: July 14/81
LOCATION: Swiftsure bank
DEPTH: 110meters
SPEAKER DEPTH: 11meters
OUTPUT LEVEL: 55dB re 1µBar at 1m

	Period	Coho	Pink	Chinook
ON	10:00-10:30	2	1	0
OFF	10:30-11:00	0	0	1
ON	11:00-11:30	1	0	0
OFF	11:30-12:00	3	1	0

DATE: August 30/81
LOCATION: North end of La Perouse bank
DEPTH: 55-75meters
SPEAKER DEPTH: 13meters

	Period	Coho	Pink	Chinook
ON	17:30-18:00	2	2	1
OFF	18:00-18:30	2	1	2
ON	18:30-19:00	1	1	2
OFF	19:00-19:30	1	0	0

DATE: Sept. 2/81
LOCATION: West side of La Perouse bank
DEPTH: 82-92meters

	Period	Coho	Pink	Chinook
ON	10:00-10:30	2	0	0
OFF	10:30-11:00	0	0	0
ON	11:00-11:30	0	0	0
OFF	11:30-12:00	0	0	0
ON	12:00-12:30	2	0	0
OFF	12:30-13:00	1	0	0
ON	13:00-13:30	0	0	1
OFF	13:30-14:00	0	0	0

DATE: Sept. 3/81
LOCATION: South-east end of La Perouse bank
DEPTH: 59meters

	Period	Coho	Pink	Chinook
ON	14:30-15:00	2	1	0
OFF	15:00-15:30	3	0	0
ON	15:30-16:00	0	0	0
OFF	16:00-16:30	1	3	1
ON	16:30-17:00	3	1	0
OFF	17:00-17:30	0	0	0
ON	17:30-18:00	0	0	1
OFF	18:00-18:30	1	1	0
ON	18:30-19:00	0	2	2
OFF	19:00-19:30	2	3	2

DATE: Sept. 6/81
LOCATION: Swiftsure bank
DEPTH: 55-75meters

	Period	Coho	Pink	Chinook
ON	12:30-13:00	0	0	0
OFF	13:00-13:30	3	0	0
ON	13:30-14:00	0	0	1
OFF	14:00-14:30	0	0	0

TABLE 4-2: Salmon Catch During Cycled Playback of Test Tape II; Pulsed Low Frequency Noise

DATE: Aug. 25/82
LOCATION: Portland Point
DEPTH: 80meters
SPEAKER DEPTH: 14meters
OUTPUT LEVEL: 55dB re 1μBar at 1meter

	Period	Coho	Chinook
ON	08:00-08:30	0	0
OFF	08:30-09:00	0	0

DATE: Aug. 26/82
LOCATION: As Above

	Period	Coho	Chinook
ON	08:30-09:00	0	0
OFF	10:00-10:30	1	0
ON	10:30-11:00	0	0
OFF	11:00-11:30	0	0
ON	11:30-12:00	0	0
OFF	12:00-12:30	3	0

DATE: Aug. 28/82

	Period	Coho	Chinook
ON	16:30-17:00	0	0
OFF	17:00-17:30	0	0
ON	17:30-18:00	0	0
OFF	18:00-18:30	0	0
ON	18:30-19:00	0	0
OFF	19:00-19:30	0	0

DATE: Sept. 6/82
LOCATION: North side of Juan de Fuca Canyon
DEPTH: 130-200meters

	Period	Coho	Chinook
ON	09:30-10:00	2	0
OFF	10:00-10:30	4	0
ON	10:30-11:00	1	1
OFF	11:00-11:30	4	1
ON	11:30-12:00	2	0
OFF	12:00-12:30	3	1

DATE: Sept. 7/82

	Period	Coho	Chinook
ON	15:00-15:30	1	0
OFF	15:30-16:00	1	0
ON	16:00-16:30	0	1
OFF	16:30-17:00	0	0
ON	17:00-17:30	1	0
OFF	17:30-18:00	0	0

DATE: Sept. 15/82
LOCATION: La Perouse bank
DEPTH: 80meters

	Period	Coho	Chinook
OFF	16:30-17:00	2	0
ON	17:00-17:30	4	0
OFF	17:30-18:00	3	1
ON	18:00-18:30	4	0

TABLE 4-3: Salmon Catch During Cycled Playback of Test Tape III; Feeding Sounds of Large Rainbow Trout

DATE: Sept. 9/82
LOCATION: Swiftsure bank
DEPTH: 100meters
OUTPUT LEVEL: 55dB re 1μBar at 1m

	Period	Coho	Chinook
ON	14:30-15:00	0	0
OFF	15:00-15:30	1	0
ON	15:30-16:00	2	0
OFF	16:00-16:30	2	0

DATE: Sept. 16/82
LOCATION: La Perouse bank
DEPTH: 80meters

	Period	Coho	Chinook
ON	16:00-16:30	3	0
OFF	16:30-17:00	0	1
ON	17:00-17:30	1	0
OFF	17:30-18:00	2	0
ON	18:00-18:30	0	1
OFF	18:30-19:00	2	0

As a footnote to the playback trials, John Ford of UBC conducted preliminary playback experiments of recorded killer whale sounds to the subject pods in Johnstone Straits during the summer of 1982 (John Ford pers. comm.). He used the same sound projector (the Aquavox UW 60) employed in these experiments. Strong reaction to the sounds was evident, with some individuals becoming extremely agitated, approaching the sound at high speed, and actually bunting his vessel. This is at least an indication that the equipment is capable of producing sounds of a biologically meaningful level and character in field conditions.

4.5 GENERAL DISCUSSION

The predominant sounds in the fish recordings were the periodic broadbank pulses evident in the sonograms (Figs.3-8, 4-7, 4-8). These ranged approximately 0.1-8kHz for herring, 1.5-7kHz for coho (1-2.5kg) and 0.15-3.5kHg for rainbow trout. The source of these sounds is uncertain but some speculations follow.

The herring were relatively silent until the school piled into a corner of the net pen. The "knocking" sounds then occurred as the fish became active, thrashing and occasionally splashing as they attempted to reverse direction. Franz (1959) measured the underwater noise associated with the impact of water droplets on the surface. He found that two mechanisms were responsible; a sharp pulse results from the initial impact, followed by sounds emitted by pulsation and collapse of entrained air bubbles. The acoustic spectrum he measured was wide, 0.5-10kHz with maximum sound pressure levels at the lower end. Fig.3-6, the sonogram of Test Tape I shows the character of these sounds. Observation during acoustic monitoring of the swimming herring revealed that surface splashing, while undoubtably a contributor to the herring sounds recorded, did not always correlate with the occurrence of the "knocks". Another explanation is required, particularly as the same type of sounds, although lower in pitch were evident in the coho, chinook and rainbow trout recordings where surface splashing was not observed during sound production.

Cavitation noise is a common source of broadband noise in the sea, usually associated with ship's propellors. Ross (1976) estimates that 80-85% of the acoustic energy projected from a vessel at speed results from cavitation. This occurs when the local pressure near a body in motion relative to the medium is lowered to or near the value of the static pressure. Rupture occurs, resulting in a microscopic bubble containing water vapor and dissolved gases. Most liquids, and particularly sea water in the mixed layer, contain many microscopic and sub-microscopic voids which act as cavitation nuclei. These effectively reduce the tensile strength of the liquid, allowing cavitation to occur at negative pressures above the actual static pressure. The collapse of cavitation bubbles as they reenter regions of higher pressure results in radiation of broadband noise. This can reach 30dB re 1μbar in the region 1-10kHz (Barker 1973). If cavitation caused the observed broadband pulses, actively swimming or feeding fish must be capable of transiently lowering the pressure to near ambient levels. Examination of filmed fusiform fish movements during turning and rapid start manoeuvres (Weihs 1972, Webb 1976), points to movement of the caudal fin as a possible source. Tip speeds of 6m/s were recorded during fast starts of small rainbow trout (<500gm) by Webb (1976). A relation used in marine design (and elsewhere) in calculation of cavitation inception conditions is the cavitation equation;

where,

$$\sigma = \frac{Po-Pv}{\frac{1}{2}\rho u^2}$$

σ =cavitation number
Po =ambient pressure
Pv =vapor pressure of sea water at relevant temperature
ρ =density of seawater
u =speed

A velocity of about 10m/s near the surface at 30°C gives a sigma of 2, about the upper limit for onset of cavitation of a hydrofoil at a high angle of attack (Morgan 1969). The rise in P_O with increasing depth requires an increase in u to achieve a constant sigma, precluding cavitation at depth if an animal cannot produce the requisite speed at the surface. There is no information in the literature on the quick-start and manoeuvring abilities of Pacific salmon, however given that small rainbow trout (similarly shaped fish) could attain caudal fin tip speeds approaching the required 10m/s, salmon may be similarly able.

Certain cetaceans are capable of speeds (11m/s) in the region of cavitation onset (Lang 1975). Tail speeds will be somewhat higher. Fig.4-9 is a sonogram of killer whales (Orcinus orca) actively feeding on salmon (provided by John Ford). These are sounds associated with rapid accelerations in pursuit of the elusive prey (John Ford pers. comm.). The broadband character of the sounds indicate that cavitation may be the source. It should be noted that the whales did not break the surface during the recording.

Another possible source of cavitation noise in salmon (and other fish and cetaceans) is suction feeding. Because of the relative size difference between predator and prey, water

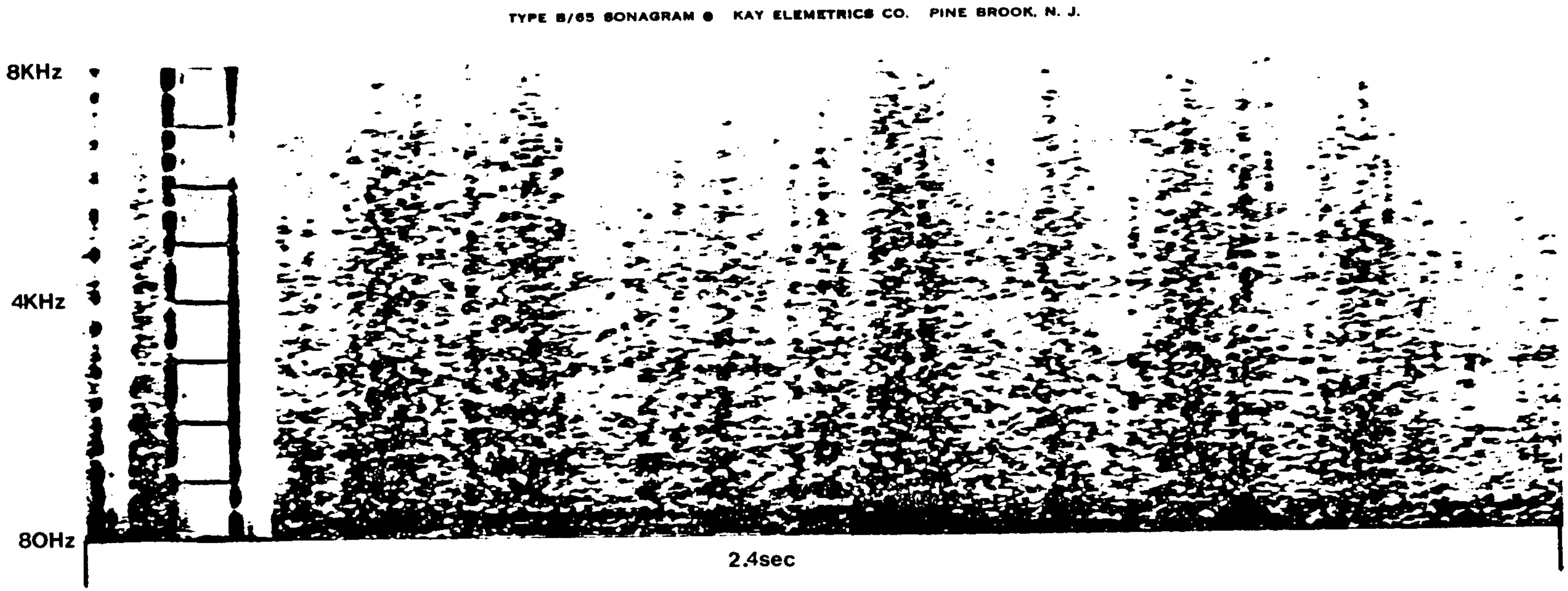

FIGURE 4-9. Sonogram of killer whale (Orcinus orca), tail beats during rapid acceleration. The whales were actively feeding on salmon in the Straight of Juan de Fuca, near Sheringham Point(recording courtesy of John Ford). Filter bandwidth 45 Hz.

movement from the predator's approach affects the position of the prey. Suction created by rapid extension of the mouth cavity is used by most teleost fish to overcome this effect and draw the prey into the jaws (Lauder 1980). Buccal cavity pressures of -650cm H_2O have been measured in sunfishes (Lauder 1980). This represents about 64% of the negative pressure theoretically required (-1020 cm H_2O) to cause cavitation at the surface. Salmon utilize a combination of suction and forward body movement in prey capture and although they probably cannot develop negative pressures from mouth expansion approaching the slower sunfishes, the additive effect of body velocity and suction may be sufficient to induce cavitation.

Whatever the source of the broadband pulses evident in the recordings of various fish, these were certainly the loudest and likely the most significant sounds observed. They may be analogous to the "veering" sounds of Moulton(1960) with anchovies and the "thumps" Stober (1969) observed in cutthroat trout. Sonograms of these sounds showed the same broadband character. The similarity between this class of sounds made by salmon and the cavitation noises made by damaged or unbalanced propellors (Fig.4-2), and killer whale tail beats (Fig.4-9) may be the source of the varying fishing performances in salmon trollers that has been associated with sonic output.

5.0 CONCLUSIONS

Towards understanding the role of sound in the B.C. troll salmon fishery, this study showed that:

1/ The sound spectrum produced by troll vessels coincides with the probable hearing range of Pacific salmon within the approximate limits of 20-500Hz.

2/ The sound output level of troll vessels is about 20dB re 1μbar at 1m in the absence of drive train noises. Cavitation noise from a faulty propellor or ventilation during rough weather would increase this level.

3/ The maximum detection distance of a troll vessel by a Pacific salmon is at least 30m.

4/ The predominant sounds made by actively feeding salmonids are broadband pulse dubbed "knocks". These may result from cavitation induced by tailbeats or by suction feeding.

5/ Playback of various pulsed low-frequency and recorded salmonid feeding sounds at a high level to captive salmonids in net pens and to wild fish from within the gear array of a commercial salmon troller had no observable effect on the captive fish nor did it significantly affect the catch rate of the troll vessel.

Although the study failed to establish the cause of, or substantiate the part sound plays in the troll salmon fishery, some insight into the problem was gained. It now seems more likely that the effect of boat noise is repulsive or inhibitory to the salmon due to similarities with predator sounds. Some recommendations for future studies in this area are offered in the following section based on points that arose in these investigations.

6.0 SUGGESTIONS FOR FUTURE WORK

A number of points have emerged from this study that are deserving of further work.

1/ Playback at sea with an underwater video camera mounted on the sound projector. The camera would allow direct observation of fish attracted to the sound source. A lure might be towed from the apparatus within the camera's field to provide a visual focus for incoming fish.

2/ Playback trials at sea as performed in this study but using recorded or simulated predator sounds (marine mammals, sharks). If repulsion or inhibition were occurring catch rates during test periods would be lower than during controls.

3/ An acoustic profile-relative catch level correlational study with the troll salmon fleet such as Erickson (1979) did with the US albacore jig fleet.

4/ An attempt to correlate daily "on the bite" periods with environmental conditions such as state of the tide, light conditions and water characteristics (temperature, salinity). Log book reports or daily radio contact with the fleet could be used to delineate these periods.

5/ A more thorough examination of sound production in salmon. Evaluation of fast start capabilities, peak swimming speeds and suction feeding in salmon are needed to explore the origins of the "knocks". Recording of feeding salmon at depth should confirm if cavitation is involved.

6/ Determination of frequency-threshold curves for all species of Pacific salmon (to confirm and extend the findings of Kol'tsova *et al* 1977) is needed to accurately determine detection distances from sound sources. These data might be useful in predicting effects from industrial noise such as offshore oil exploration.

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