Hydroacoustic monitoring and feeding control in cage rearing of Atlantic salmon (*Salmo salar* L.)

Å. Bjordal
Institute of Marine Research, Bergen, Norway

T. Lindem
University of Oslo, Oslo, Norway

J.E. Juell
Institute of Marine Research, Bergen, Norway

A. Fernö
University of Bergen, Bergen, Norway

ABSTRACT: This paper describes a hydroacoustic system for monitoring and feeding control in cage rearing of Atlantic salmon.

An echo-sounder, linked to an upward-facing transducer mounted under the cage, provides echo signals from the caged fish. The signals are processed by a PC-based echo integrator which monitors the change in echo intensity at different depths in the cage. Before feeding the highest fish densities are found at medium depths. When feeding starts, fish density and thus echo intensity close to the surface increase significantly and stay at a high level as long as the appetite remains high. When the echo intensity in the upper layer of the cage decreases to a certain preset threshold, the feeders are automatically shut off. The downward migration of the fish, as shown by the reduced echo intensity, is thus used as an indicator of satiation.

Besides the direct feeding control application, amount of feed is logged, and the software allows different feeding strategies for example with respect to number of daily feedings, feeding intensity, total daily feed limits, and level of automation to be implemented. The system is designed to monitor and control twelve cages and feeder units.

Other useful applications as continuous monitoring of the fish with possible alarm functions, observation of dead salmon and wild fish, as well as possible biomass estimation, are described and discussed.

1 INTRODUCTION

During the past two decades, the rearing of salmon in sea cages has developed from the trial stage into an important industry. As in any industry, the profitability of salmon farming depends on good monitoring of the production process. In cage rearing of salmon, monitoring of the fish is still usually a matter of visual inspection at the surface. Particularly with the development towards larger and deeper cages, there is a clear need for more sophisticated techniques for continuous monitoring of the fish.

Hydroacoustic technology is widely used for fish finding, fish monitoring, and biomass estimation of fish stocks, and advanced echo sounder and sonar equipment is commonly used, even on the smallest fishing vessels. Since the first attempts to use hydroacoustics for monitoring the behaviour of salmon in sea cages (Bjordal et al. 1986), a number of studies have revealed the usefulness of this technology for different applications. Various targets and events can be observed hydroacoustically, e.g. the distribution of the salmon including vertical and horizontal movements, dead salmon, wild fish outside the cages, feed pellets, feed waste, and cage webbing. Studies of the acoustic characteristics feed pellets (Juell, 1991) led to the development of a feeding control system based on registration of feed pellets at medium cage depths (Juell et al. 1993a).

It has also been shown that hydroacoustic methods are ideal for monitoring changes in vertical fish distribution under different environmental conditions (Fernö et al. subm.), and a hunger-dependent change in vertical distribution during feeding was revealed (Juell et al. 1993b). When feeding starts, the salmon typically rise towards the upper part of the cage with a subsequent descent as hunger is reduced. This change in behaviour can easily be quantified through echo integration at different depth layers of the cage, and the signals can be used to control feeding to suit the appetite of the fish.

On the basis of this characteristic behaviour, a system for automatic feeding control has been developed. In this paper the system is briefly described,

P.O. Box 1870, N-5024 Bergen, NORWAY

some typical results are given, and further applications of the technology are discussed.

2 SYSTEM DESIGN

The design of the system ("Cage Eye") is based on standard echo-sounder technology (Fig. 1). An upward-facing transducer, suspended under the cage, emits sound pulses and receives the echo signals from different targets, such as fish, cage bottom and sea surface. The echo signals are fed to the PC-based echo integrator, and may be displayed either as a simple colour echogram or in various post processed modes. The system includes multiplexing for monitoring and feeding control of several cages, at present up to twelve units. Modem connection offers the possibility of remote operation of the system, as displays and controls can be transferred to a remote personal computer.

The proportion of the cage volume covered by the acoustic beam is determined by the beam width of the transducer and its depth relative to the cage. In this study, a Furuno wide beam (42°) transducer was used, giving a good coverage of the upper 5 m of the cage. An acoustic pulse length of 1 ms was used, giving a resolution of approximately 1 m. This relatively coarse resolution is not ideal for detection of single fish echos, but has been found suitable for monitoring gross changes in vertical fish distribution. The pulse length can easily be changed if better resolution is desired.

In case of power failure, the system is run on battery backup with an UPS which will keep the system running for 30 min. All files are saved and the system is shut down when 20% of the battery power is left.

The echo sounder was designed at the Department of Physics, University of Oslo. The transmitter can be programmed to provide an output power of 5 to 100 W. The receiver has a time-varied gain (TVG) function at the input stage to compensate for the geometric spreading of the acoustic energy. Compensation for the absorption caused by water salinity and the large biomass of fish in the cage is done by computer analyses of the echo signals. To avoid saturation, due to the large biomass in the cages, relatively low acoustic power (10 W) was chosen.

Special care has been taken to acoustically identify and exclude the surface echo. This is important because most fish normally feed close to the surface, and surface echos must not be included in the echo integrations.

The system has different applications: routine observation of fish distribution including identification of alarming changes, registration of dead fish on the bottom of the cage and of wild fish under the cages, and feeding control. The last application is emphasized here. For feeding control, the system can be operated in three modes:

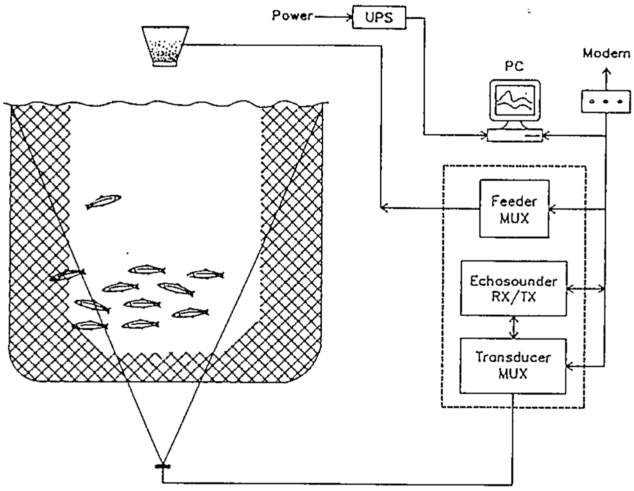

Fig. 1 Basic sketch of the CAGE-EYE system design. (UPS: uninterrupted power supply; MUX: multiplexer; RX/TX: receiver/transmitter)

Fully automatic feeding. The number of daily feedings is preprogrammed. When feeding starts, the response of the fish is reflected in changes in echo abundance at different depths. If a sufficient number of fish respond by ascending, the feeding is continued until the echo abundance in the upper layer falls to a preset threshold level (Fig. 2). The computer calculates the daily and total amount of food given in each cage.

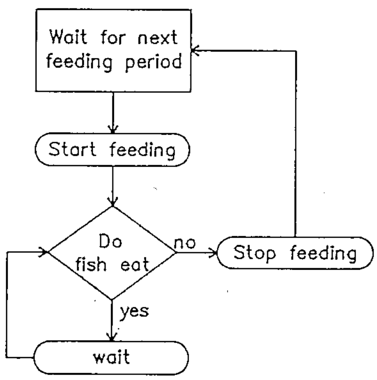

Fig. 2 Flow chart for the fully automatic feeding algorithm.

The fish distribution (echogramme) for several cages can be displayed simultaneously. Since the transducer is located some meters below the cage, dead fish on the cage bottom can easily be detected. This distance between transducer and cage bottom also allows detection of wild fish under the cage, a typical indication of feed waste.

Interactive feeding. In this mode, the feeding is controlled by the PC-operator that terminates the feeding based on visual inspection of the displayed fish distribution in the cage.

Feeding according to feeding charts. In this mode, the system operates as a standard PC-based feeding system, based on food rations calculated from estimated biomass, water temperature and expected growth. The system also includes a production log for accounting the number of fish taken out of the cage and food consumption.

3 SYSTEM APPLICATIONS AND RESULTS

During the development phase, the system was tested at Austevoll Aquaculture Research Station and for shorter periods at different fish farms. To illustrate applications of the system, some examples are given from the first long-term trial in commercial cage rearing. From 9 October 1991 - 10 February 1992, the system was used to monitor three 8 m deep square cages (15*15 m), each stocked with about 30 000 salmon. The transducers were positioned at 15 m depth and the acoustic beam covered the area of food dispersal.

At first, only fish behaviour was monitored, while the fish were fed continuously with automatic feeders (Betten) during most of the day. Figure 3a shows the typical diel variation in vertical distribution during this period. The fish were relatively evenly distributed throughout the cage at night, however, with most fish in the upper part of the cage. At dawn the fish descended. When feeding started the whole group rose and concentrated mainly in the uppermost 2 m. Towards the end of the feeding day, fish density near the surface usually decreased, indicating reduced appetite. Occasionally, aggregations of wild fish were observed under the cage at this stage, indicating that food was being wasted (Figure 3a). When feeding had finished, most

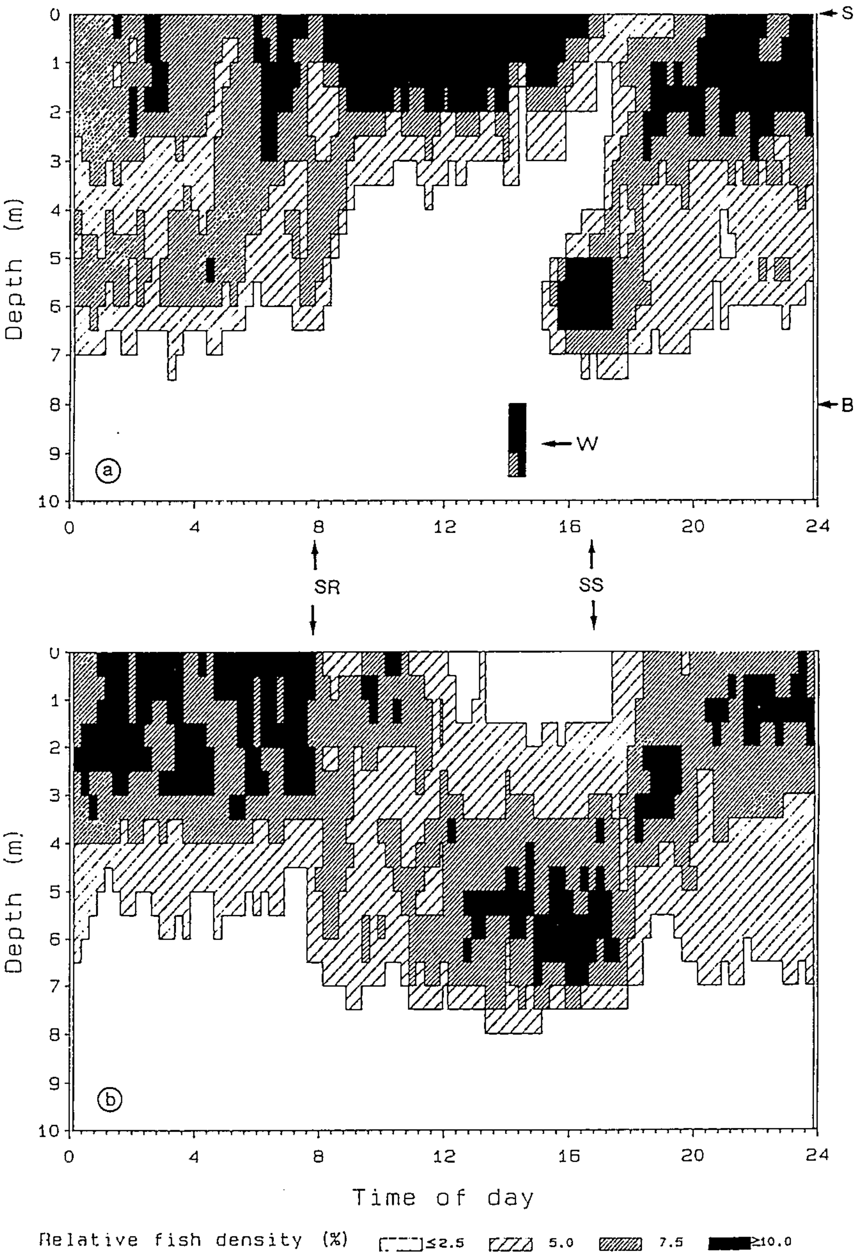

Fig. 3 Diel pattern of vertical distribution of about 30 000 Atlantic salmon in a sea cage, (a) prior to and (b) after adaptation to automatic feeding control. Time of sunrise (SR) and sunset (SS), water surface (S), sea cage bottom (B) and wild fish (W).

of the fish descended to 5-7 m depth, and after sunset the fish gradually rose and showed a more even vertical distribution.

After three weeks the hydroacoustic system was set to automatic feeding control. Feedings were initiated at 10.00, 12.00 and 14.00 hours, and the feeding intensity (food · $fish^{-1}$ · $time^{-1}$) was increased considerably. If the initial response (change in echo intensity near the surface) to the food was weak, feeding was immediately terminated. If a strong initial response indicated high hunger level, feeding was continued until reduced appetite was indicated by the fish descending (Fig. 4). The fish took some time to adapt to the new feeding regime, but eventually changed their behaviour markedly. This change in behaviour is reflected in the typical vertical distribution after adaptation (Fig. 3b). The fish now spent most of the day deeper in the cage, only entering the upper part of the cage during the short feeding periods. Most of the food was normally eaten during the first meal and the initial response in later meals was often too weak for feeding to be continued.

Daily food intake varied considerably in all cages, and periods of low and high appetite often coincided in all three cages (see Figure 5). This short-term variation is considerably greater than was predicted by feeding charts which only compensate for variation in fish size and temperature. During the trial period, average fish weight increased from 0.43 kg to 1.03 kg and sea temperature gradually decreased from 12 to 6 C°. The average specific growth rate was 0.7 (% wet weight/day) and the average food conversion ratio was 0.96 (food/weight gain).

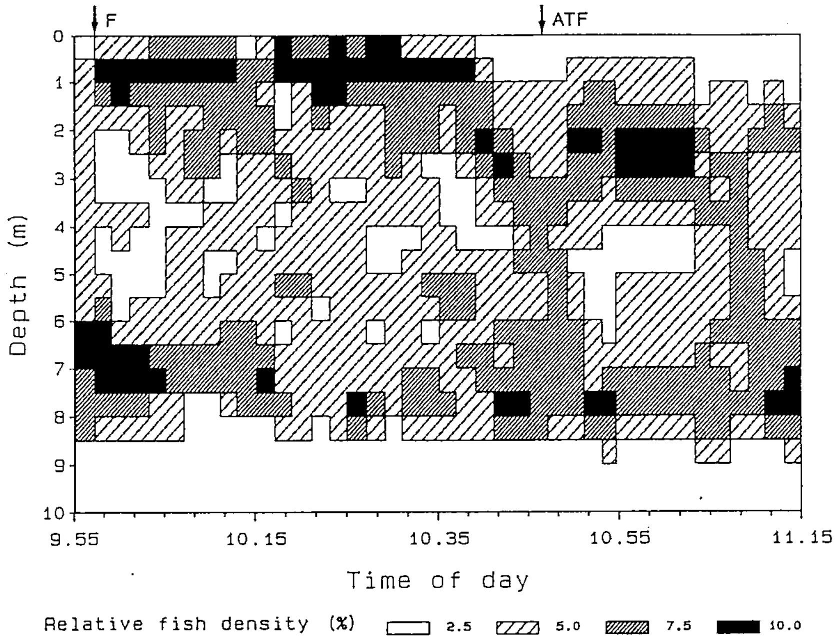

Fig. 4 The change in vertical distribution during feeding. The start of feeding (F) and automatic termination of feeding (ATF) due to descent of the fish are indicated.

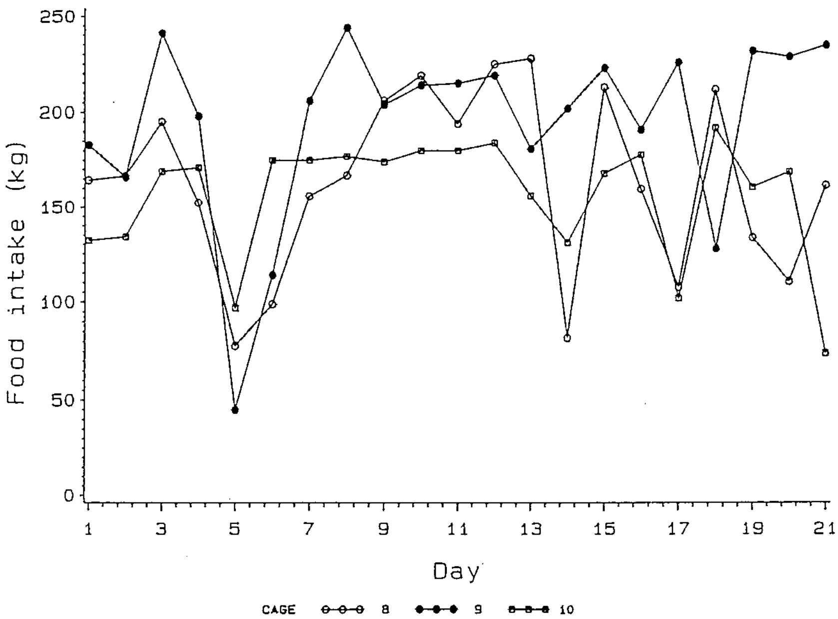

Fig. 5 Daily food consumption in three cages with about 30 000 Atlantic salmon during a three week period when food rations were automatically controlled by monitoring fish behaviour.

4 DISCUSSION

The hydroacoustic system described here can record both horizontal and vertical movements of caged fish. When the acoustic beam fully or partly covers the area of food dispersal in the cage, a representative estimate of the vertical fish distribution is obtained, and the proportion of fish within the beam also provides an estimate of the horizontal distribution. As the main purpose for general monitoring and feeding control is to estimate the relative fish distribution, problems with echo variations caused for instance by variations in swimbladder volume, are of little importance. Saturation of the receiver system at high densities should not occur with the acoustic power output effect chosen.

The main application of the system is automatic feeding control. By utilizing the correlation between downward fish movements and decreasing hunger level, the fish can be fed to satiation with low risk of food waste. This dynamic method of regulating food rations is superior to fixed feeding regimes based on feeding charts, because of the marked fluctuations in appetite observed in this study and by Juell et al. (1993c). Feeding control is accomplished via demand feeding of the total cage population in contrast to demand feeding techniques that are based on the response of individual fish (e.g. Tipping et al. 1986). Automatic control is most readily obtained if the fish stay relatively deep before feeding and gradually return to this depth during the course of feeding. However, this principle is also valid when the fish show a more shallow distribution, provided that there is room for upward movement at the start of feeding. The supplementary use of absolute limits of amount of food given per meal set from feeding charts makes the system even safer, and the risk of wasting food should be negligible.

Downward migration has been observed both at high and low feeding intensities (Juell et al. 1993b; Fernö et al. submitted). However, fewer feedings at high feeding intensity give more marked changes in fish distribution. By giving few, concentrated feedings in the morning and evening, the fish can be fed at the times they prefer to feed (Kadri et al. 1991). The present study demonstrates that with a change from frequent to infrequent feeding, salmon that stay close to the surface during the day eventually change their distribution and stay deeper except during the concentrated feeding periods. This could be advantageous, as salmon in pens seem to avoid the surface at high light levels, probably because of a greater risk of predation and the damaging effect of UV-light (Juell et al. 1993b; Fernö et al. subm.).

The system should be used to feed the fish to satiation or relatively close to that point, otherwise competitively inferior fish could be underfed. If there is a need to modify the quality of the fish, for instance to decrease the visceral and muscular fat levels (Storebakken et al. 1991), this can be done by periodic starvation.

A second application of the hydroacoustic system is to regularly monitor the behaviour of fish in pens in order to optimize rearing conditions. There is an increasing need to monitor salmon in cages, particularly in connection with the increasing use of large rearing units. By observing fish distribution under different conditions throughout the year, basic knowledge about characteristic behaviour patterns can be acquired. Deviations from normal behaviour may indicate suboptimal conditions (e.g. early stages of disease or algal blooms), and thus a kind of fish-man communication can be established. Downward flights caused by people or predators can be used to assess the stress level of the fish. Alarms that are released when fish are disturbed at night, during thefts for example, could also be constructed. Monitoring by hydroacoustic systems can be supplemented by ultrasonic telemetry technology, using increased heart rate as an indicator of stress (Bjordal et al. 1988).

A further application is biomass estimation, based on echo integration in periods when the fish are evenly distributed - e.g. at night (see Fig. 3a).

The suggested use of hydroacoustic monitoring and feeding control provides valuable information for optimizing the production of salmon with the following clear advantages: reduced pollution caused by negligible food waste, reduced risk of spreading antibiotics to wild fish, reduced costs due to a better feeding control and reduced manpower in fish feeding. Early warning of diseases and changes in environmental quality, and full remote monitoring and control by modem also represent clear advantages for improved production control in cage rearing of salmon.

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