PRELIMINARY INVESTIGATIONS INTO THE RESPONSE OF 0+ TWAITE SHAD (*ALOSA FALLAX*) TO ULTRASOUND AND ITS POTENTIAL AS AN ENTRAINMENT DETERRENT

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1 INTRODUCTION

Water is abstracted from riverine, estuarine and marine environments to supply potable water, power stations, hydroelectric facilities and industry. Such abstractions inevitably carry with them the risk of fish entrainment, defined as 'the drawing in of fish of any life stage at a water intake' (Turnpenny & O'Keeffe, 2005). It is possible, however, that entrainment losses can be reduced to an acceptable level with the use of appropriate fish screening technologies.

Fish protection solutions for water intakes are manifold and include: alterations to intake design; management of the abstraction regime; modification of existing screens to make them "fish friendly"; provision of fish return systems; and the installation of physical screens or behavioural deterrents to prevent or minimise entrainment. There are however a range of site specific constraints which influence the suitability of each solution.

One major consideration is the species and life stage to be protected. The handling of delicate and sensitive species such as shad (Shrimpton *et al*., 2001 cited in Zydwelski *et al*., 2003) require positive exclusion (either physical or behavioural) at the point of abstraction. Any form of mechanical handling or physical contact with screen/fish return system surfaces may result in high percentage mortalities for sensitive species and life stages.

For physical screening solutions the mesh aperture size required for the positive exclusion of small fish combined with a requirement for a low through-slot velocity is likely to result in the need for a screen structure of large physical size. Additionally the head loss across such fine mesh screens can result in operational difficulties and an increase in pumping costs.

In certain circumstances behavioural deterrents (e.g. light, sound, electricity) can be employed to substitute for or supplement physical screening. Behavioural fish deterrents operate by evoking an avoidance response in the target species to one or more stimuli, resulting in the fish avoiding the area from which the stimulus is being projected.

Although a number of behavioural screening technologies have proven to be effective in excluding fish from intakes they rarely achieve the same exclusion efficiency as physical screens of an appropriate mesh aperture, which with careful design, operation and maintenance can be 100% effective. The most commonly employed and well understood of the behavioural screening technologies is low frequency sound (20 Hz to 500 Hz), while infra sound (<20 Hz) light and electric screens have also achieved good results in certain circumstances.

While some in-river engineering may be required during retro-fitting of behavioural screening technologies this is generally minor in comparison to the civil works required during the installation of fine mesh physical screening solutions.

2 TWAITE SHAD

The two UK shad species; allis (*Alosa alosa*) and twaite (*Alosa fallax*) are protected under Annex II of the European Habitats Species Directive and as such require entrainment protection measures where the integrity of populations are deemed to be at risk. Twaite shad are an anadromous species which as adults migrate from the sea to rivers and, spawn in freshwater during June and July. Young of the year shad commence their downstream migration as larvae just days after emergence from spawning gravels. At less than 50 mm in length and with a burst swimming capacity of between 20 to 25 cm s^{-1}, these seaward migrating individuals are susceptible to entrainment throughout the riverine, estuarine and marine phases of their migration.

Twaite shad of all ages are susceptible to handling mortalities and losses are commonplace after physical contact with nets or screens (S. Clough *pers obs*). Consequently screens to prevent entrainment of young of the year shad need to provide positive exclusion without handling at the point of abstraction. The mesh aperture size required for the physical screening of these individuals ranges from potentially 1 mm (larvae) to 3 mm (juveniles) depending on the developmental stage requiring protection. Due to the limited swimming ability of these life stages, an escape velocity of 23 cm s^{-1} or lower is generally advised for their protection (Turnpenny & O'Keeffe, 2005; O'Keeffe & Clough, 2008). The screening options for juvenile shad are therefore either fine mesh aperture (c. 3 mm) positive exclusion physical screens or a behavioural deterrent.

2.1 SHAD HEARING

Clupeiformes including shad are classed as hearing specialists which not only have a swimbladder but also a connection between it and the inner ear which can extend the upper end of their hearing threshold by several kilohertz (Higgs *et al*., 2004 & Popper *et al.,* 2004). Consequently shad and other Alosids can detect sound of far higher frequencies than other hearing specialists (>3000 Hz).

A number of studies have been undertaken to determine the sensitivity of clupeid fish to ultrasound including adult and juvenile American shad (*Alosa sapidissima*) (Higgs *et al*., 2004, Mann *et al*., 1998 & 2001, Plachta *et al*., 2003, Plachta & Popper, 2003 and Popper *et al*., 2004). These studies have demonstrated that clupeid fish, including Alosids, can detect ultrasound at frequencies of up to 180 kHz. During the presentation of ultrasound to schools of adult American shad at different frequencies and amplitudes Plachta and Popper (2003) observed different behavioural responses. Behavioural responses were limited at all frequencies projected at sound levels less than 160 dB re 1µPa, mild reactions were observed at the onset of sound at sound levels of 175 dB re 1µPa for frequencies within the range 30 to 120 kHz. Rapid and directional behavioural responses were observed at frequencies between 70 and 110 kHz when presented at sound levels between 175 and 184 dB re 1µPa. At sound levels of greater than 185 dB re 1µPa panic like, nondirectional behaviour was observed at frequencies of between 30 and 150 kHz. The development of ultrasound detection in American shad was investigated by Higgs *et al*. (2004) through the assessment of behaviour and auditory brain stem response (ABR) of larvae within the size range 30 to 100 mm. The greatest response was observed at a sound frequency of 90 kHz at a projected sound pressure level of 140 dB re 1µPa. American shad however, do not appear to detect low frequencies as well as other hearing specialists (Popper *et al*., 2004).

It has been suggested by a number of authors that the ability of Alosids including shad to detect ultrasound has evolved to assist in avoiding predation by echo-locating predators (Astrup, 1999, Mann *et al*., 1998, Plachta & Popper, 2003 and Popper *et al*., 2004). Clupeids including Alosids during their estuarine and marine life stages are a prey source for odontocete cetaceans (toothed whales) including dolphins and killer whales (Domenici *et al*., 2000). Odontocete cetaceans emit high frequency click signals ranging from less than 40 kHz to greater than 130 kHz. Studies of the echolocation signals of odontecete cetaceans have determined centre frequencies of between; 24 to 86 kHz with an overall average of 56 kHz for Risso's dolphin (*Grampus griseus*), 40 and 50 kHz for killer whale (*Orcinus orca*), 40 and

110 kHz for Atlantic spotted dolphin (*Stenella frontalis*) with energy peaks between 50 and 60 kHz, 80 and 100 kHz for dusky dolphin (*Lagenorhynchus obscurus*), 90 and 110 kHz for white-beaked dolphin (*Lagenorhynchus albirostris*) and peak to peak frequencies of between 125 and 130 kHz for harbour porpoise (*Phocoena phocoena*) (Au *et al*., 1999, Au, 2003, Au & Herzing, 2002 and Phillips *et al*., 2002). Click frequencies are often bi-modal with two prominent energy peaks. Risso's dolphin signals for example exhibit peaks between 30 and 50 kHz and 80 and 100 kHz (Phillips *et al*., 2002) and wild Atlantic spotted dolphin exhibit high frequency peaks greater than 80 kHz as well as low frequency peaks less than 40 kHz (Au & Herzing, 2002).

The specialist hearing ability and strong avoidance response demonstrated by Alosids suggests that ultrasonic acoustic behavioural deterrents could represent a species specific screening solution to prevent the entrainment of young of the year twaite shad. The hearing thresholds of larval and juvenile twaite shad are not however currently known. On this basis a series of preliminary investigations were carried out to determine the sensitivity of larval and juvenile twaite shad to ultrasonic sound frequencies, and to test whether ultrasound could be used to elicit an avoidance response in these fish and subsequently guide them in a particular direction.

3 ACOUSTIC DETERRENT FEASIBILITY INVESTIGATIONS

3.1 METHODS

Wild young-of-the-year twaite shad of between 14 to 38 mm with an average of 22 mm were collected from the River Wye during the months of July to August 2008 using an adapted seine netting technique. Following the larval fish definition given by Penaz (2001), the majority of captured individuals were determined to represent the larval life stage.

3.1.1 Threshold Response Tank Trials

Behavioural trials were undertaken within a tank to determine the hearing threshold of young-of-the-year shad. The method of sound presentation followed that used by Higgs *et al*. (2004) on juvenile American shad. This method consisted of presenting sound bursts of different frequencies to the fish for a period of 3 seconds followed by a 5 minute rest period with sound off. Sound bursts were presented in a step wise order commencing at 5 kHz intervals between 10 and 80 kHz followed by 10kHz interval steps to 110 kHz. Two cycles were completed; increasing step wise through the frequencies, and then decreasing step wise. Sound bursts of approximately 50 ms duration were generated. Sound pressure levels (Vpp) were measured using a precalibrated hydrophone. At each position within the tank over 100 consecutive pulses were analysed for peak to peak, rms (root mean square sound pressure level) and SEL (Sound Exposure Level) levels. These measurements were then converted to dB re 1µPa.

Fish behaviour was recorded throughout the trial period using a colour video camera (Aquacam) and digital hard drive. The behaviour of each fish was subsequently tracked using specialist motion tracking software (Simi Motion) for a period 3 seconds before and during the 3 seconds of sound presentation. Calibration of the video output enabled data to be generated for; distance travelled by each fish (m), velocity of movement (ms^{-1}) and acceleration (ms^{-2}).

3.1.2 Avoidance Response Flume Trials

To investigate active avoidance in addition to response to sound projection, trials were also undertaken within a choice chamber set-up inside a flume channel. Transducers were positioned at the entrance of each of the two channels with sound being emitted continuously. Sound projection was altered between the two channels and control tests were undertaken with no sound projection.

Fish passing down each of the two channels were recorded. Their behaviour within the flume and in particular at the point of sound projection was further monitored through the placement of colour video cameras at key points along the flume length. As with the response trials, specialist motion tracking software (Simi Motion) was used to track fish movement.

3.2 RESULTS

3.2.1 Threshold Response Tank Trials

A hearing response was classified as a significant difference between both distance moved and velocity of one or more fish prior to and during sound presentation. Positive significant reactions were observed at sound frequencies of between 30 and 60 kHz. The greatest reaction was observed at a sound frequency of 45 kHz which was presented to the fish, on average, at a sound level of approximately 198 dB re 1 µPa. The frequencies within the response threshold were those presented to the fish at the greatest sound pressure levels. It is possible therefore that startle responses may also be exhibited at other frequencies, if presented at higher sound pressure levels.

For juvenile American shad the greatest response was seen at a frequency of 90 kHz presented to the fish at a sound pressure level of 140 dB re 1 µPa (Higgs *et al*., 2004). During this investigation the most dominant harmonic for the 45 kHz pulse was at 90 kHz. No response was observed however for the 90 kHz target frequency which was presented to the fish at a greater sound pressure level than the harmonic suggesting that the observed reaction was likely to have been elicited by the main frequency (45 kHz), or a combination of frequencies, rather than the harmonic alone. A harmonic caused by transducer resonance frequencies within the region of 40 to 50 kHz was in fact observed at varying sound pressure levels at all frequencies tested (within the range of 100 to 170 dB depending upon target frequency).

The observed amplitude levels varied for each of the frequencies. The lowest observed peak + sound pressures were observed at 10 and 100 kHz. The greatest sound pressure levels varied between the 40 and 45 kHz frequencies with a peak + sound pressure level of approximately 207 dB at a frequency of 40 kHz. The pressure spectral analyses of the pulse only for each of the frequencies indicated that the transducer was being driven below its resonance for frequencies less than 45 kHz. For the lower frequencies (10, 15 and 20 kHz) the peak energy was at frequencies of between 40 and 50 kHz as opposed to the target frequencies and high energy harmonics were also seen at frequencies of between 80 and 90 kHz. At frequencies greater than 25 kHz the drive frequency became the dominant component although harmonics were still present at lower energies. At a frequency of 45 kHz the drive frequency was the dominant energy component.

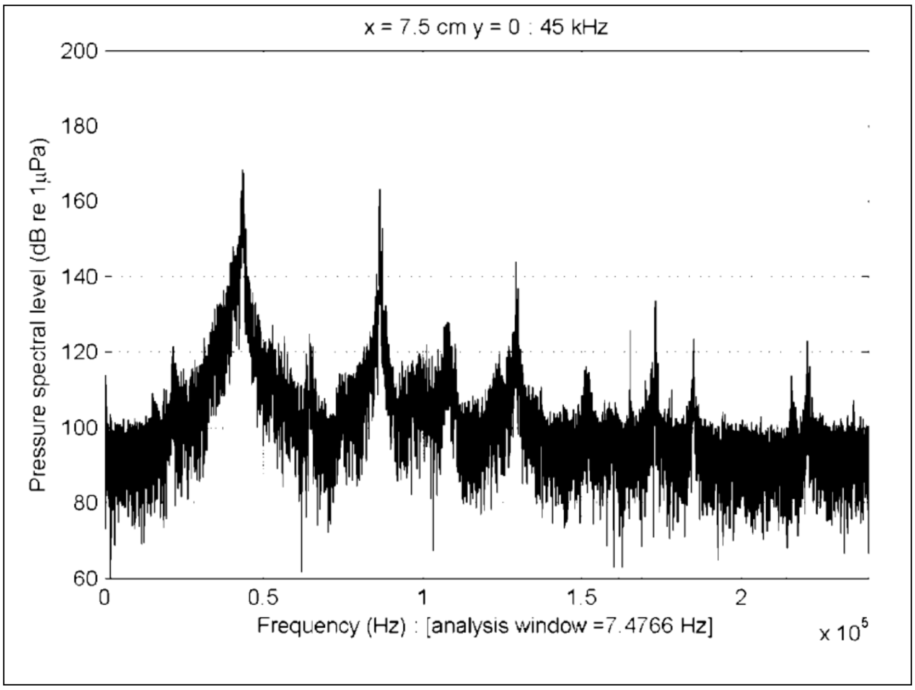

Figure 1 Example of the observed spectral levels of pulse only at a target frequency of 45 kHz

3.2.2 Avoidance Response Flume Trials

The amount of video footage collected during the trials was vast and as such it has not been possible to analyse it all to date. A portion of the video collected from a position directly above the channel split has been analysed to give an indication of behaviour in the vicinity of the sound field.

Due to limited fish stocks, flume trials at 45 kHz (determined to be the peak hearing threshold at the sound pressure levels emitted by the transducers) could only be undertaken on two occasions. The results of the first trial were the capture of 9 shad in the “sound off” channel and 1 shad in the “sound on” channel. Moreover, in total 24 passes were made by shad down the “sound off” channel in comparison to 2 down the “sound on” channel. A number of fish were observed in close proximity to the mouth of the “sound on” channel but subsequently moved away from this area, and sometimes exhibited a rapid aversive response. The results of the second trial did not show such conclusive results. The number of fish caught were evenly spread between the two channels, although a total of 8 passes were made down the “sound off” channel, in comparison to 5 down the “sound on” channel. The sound pressure levels during both trials were similar ranging from 170 to 175 dB re 1μPa across the mouth of the “sound on” channel and 156 to 167 dB re 1μPa across the mouth of the “sound off” channel. A number of control tests were undertaken with no sound projection. During these control trials shad passed down both channels with no significant preference.

4 DISCUSSION

Initial results from these preliminary studies were encouraging and indicated that young-of-the-year twaite shad both responded to and could potentially be deterred by ultrasound. Significant reactions were observed at frequencies between 30 and 60 kHz, peaking at 45 kHz. Greatest reactions were observed at an average peak + sound pressure level of 198 dB re 1μPa. Results of avoidance response experiments however remain inconclusive. Although a high percentage deflection efficiency was observed in one of the tests and no significant channel preferences were observed during the control tests, the reverse trial did not show conclusive results. The inconclusive results from the second directional test may be as a result of the slightly differing channel shape altering the sound field at the point of channel split resulting in some sound leakage into the channel upstream of the split. Further trials are therefore required before the use of ultrasound as a behavioural deterrent for the protection of juvenile shad from entrainment into water intakes can be fully considered.

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