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Sounds produced by herring (*Clupea harengus*) bubble release

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Abstract

In the herring (*Clupea harengus*), the swim bladder is connected to both the alimentary canal and the anal opening. The anterior duct is used for filling the swim bladder with air. Gas release from the anal opening is often observed when the fish is scared or during ascent and descent. Here, the sounds produced by such a gas release are studied. The fish was kept in a low-pressure chamber. As the ambient pressure was reduced, the gas in the swim bladder expanded and was emitted through the anal opening. Herring sounds were also recorded in a fish trap and in the field. The characteristic sound made by herring during gas release is denoted as the pulsed chirp. This pulsed chirp is 32–133 ms long ($N = 11$) and consists of a series of 7–50 ($N = 11$) transient pulses with a continuous reduction of the frequency emphasis (centroid frequency of first pulse 4.1 kHz and of last pulse 3.0 kHz, $N = 11$). The source level of the chirp is 73 ± 8 dB re 1 µPa rms (root mean square) at 1 m ($N = 19$). The pulsed chirp is not known to be produced by any other marine animal and may be a good fingerprint for identifying schools of clupeid fish by natural predators, fishery scientists and fishermen. A model for the generation of the pulsed chirp is presented and tested on existing data.

Keywords: Bioacoustics; Sound production; Gas release; Herring

1. Introduction

The herring (*Clupea harengus*) is quantitatively the most important fish species of northern Europe. During decades of intense research, we have learned about its migratory, diurnal and foraging behavior, and about its role in the marine food web (Klinkhardt, 1996). In spite of this, little is known about herring sound production and communication. In this study, we focus on acoustic signals produced by herring.

Compared to most other fish species, herring has excellent hearing abilities (Enger, 1967). In clupeid fish, the swim bladder connects to the inner ear, which facilitates the perception of sound. This hydro-acoustic detection system is in close contact to the lateral line canal system on the head of the fish (Blaxter et al., 1981) and works well for the perception of both acoustic pressure as well as hydrodynamic displacement signals.

Another feature of the herring anatomy is the connection between swim bladder both to the stomach and to the anal opening (Fig. 1; Bennett, 1879–1880). Herring does not seem to produce gas in the swim bladder as many other fish species do (Fahlén, 1967; Blaxter and Batty, 1984). Air is inhaled at the surface, swallowed and transported into the swim bladder through a small canal, *ductus pneumaticus* (Klinkhardt, 1996; Fig. 1).

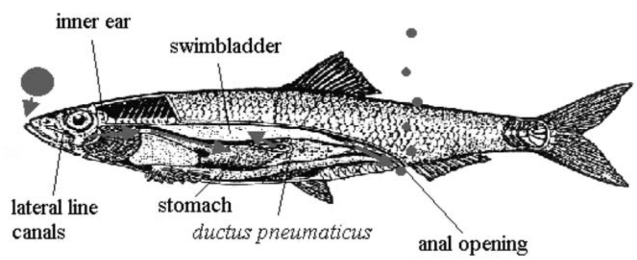

Fig. 1. The airways of herring (*Clupea harengus*). Redrawn from Klinkhardt (1996). The assumed path of air (see text) is indicated with gray circles and arrows.

It is well known among fishermen that herring schools can release air, producing clouds of bubbles that may be observed at the surface (Muus and Dahlstrøm, 1974; Thorne and Thomas, 1990; Nøttestad, 1998). Bubbles are usually released through the anal opening, connected to the swim bladder (Fig. 1). Sometimes, bubbles are released through the mouth (personal observation). Such bubbles may originate from air

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that has not yet been transferred to the swim bladder. Gas may be released both during ascent and decent and as a response to distress (Nøttestad, 1998). It has been suggested that the air release may work as an optic and acoustic screen that confuses predators (Nøttestad, 1998).

Herring is known to produce sounds (Murray, 1831; Marshall, 1962; Hering, 1964; Fish and Mowbray, 1970; Freytag, 1971; Schwarz and Greer, 1984). Previous studies performed to investigate sound production have, to our knowledge, not reported the source level of such sounds, nor have they suggested how the sounds are produced. Both these pieces of information are important to evaluate the possible function of the sound.

In this study, we report on the sound production during herring gas release. We estimate source level of herring sounds and investigate a potential sound-production mechanism.

2. Materials and methods

Herring sound production was studied with controlled experiments and field observations. The recording system consisted of a BK 8101 (sensitivity –184 dB re 1 V/µPa) and an Atlantic Research LC32 hydrophone (–202 dB re 1 V/µPa) connected via a custom-built amplifier to a Sony TCD-D7 DAT recorder (recording band width 0.1–22 kHz). Data were digitally transferred to the computer via a *U2A* digital interface (*Egosys Inc.*) and subsequently analyzed using *Matlab* (*MathWorks, Inc.*) and *Cool Edit 2000* (*Syntrillium Inc.*) software. Visual observations were made using underwater video cameras.

2.1. Low-pressure chamber (LPC)

Herring were caught live in nets on the Swedish west coast. The fish were carefully removed from the nets and transported to shore in 20 l buckets. The fish were submerged into a transparent water-filled plexi glass cylinder connected to a vacuum pump and a manometer. A hydrophone was mounted on an aluminum rig together with the fish container. The distance from the anal opening of the fish to the hydrophone was 8 cm. The hydrophone was located on the right-hand side of the fish, 90° from the sagittal plane. A custom-built housing with an underwater video camera (*Bischke*) monitored the rear end of the fish from the opposite side of the hydrophone. The rig was lowered into the harbor to a depth of 2 m (the sea floor being at more than 5 m depth). As the pressure in the fish container was decreased (down to a minimum of 0.1 bar), the air inside the swim bladder of the fish expanded and the fish was forced to release air through the anal opening. This experiment permitted sound recordings of live herring in an almost free acoustic field. Additional measurements with the pressure chamber were made in Hårsfjärden and Söderhamn on the Swedish Baltic Sea coast. A total of 20 fish were tested with the LPC. The fork length of the fish was 19.8 ± 1.6 cm (mean ± 1 S.D., $N = 17$; the length of three fish was not measured). The acoustic impedance of plexi glass is close to that of water, so that sound attenuation through the walls of the cylinder could be neglected.

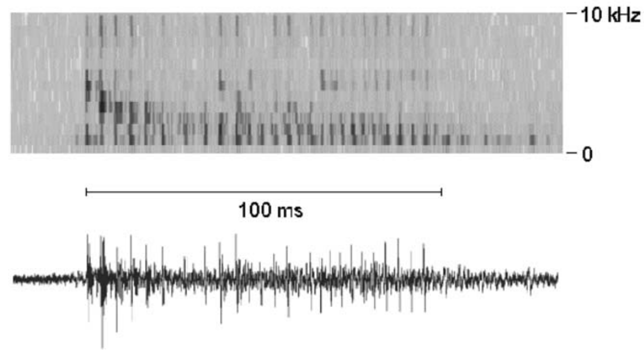

Fig. 2. The pulsed chirp of a herring, recorded in the Swedish archipelago of the Bothnean Bay during the spawning season in June. Top: Spectrogram (filter bandwidth 1.5 kHz). Bottom: Oscillogram, synchronized with the spectrogram.

2.2. Recordings at herring trap net

The only Swedish herring trap is situated close to the town of Söderhamn in the Gulf of Bothnia. This trap resembles Danish herring pond nets (von Brandt, 1964): a leader net directs the fish into a series of funnel-formed net gates that end in a 5 × 3 × 3 m bag. At the time of recording, about 4 tons of live herring were circling inside the trap. A hydrophone was lowered into the bag of the trap, together with an underwater video camera. An extra hydrophone was kept about 15 m outside the net enclosure as a control. Recordings were made in flat calm weather for two days and nights in June 1997. About 10 h of recordings were made.

2.3. Field recordings in a spawning bay

Half a kilometer from the fish trap in Söderhamn (see above), there is a 10 × 30 m bay with a maximum water depth of 2–3 m. This bay is known to be a spawning site of herring. During the spawning season in early June 1997, we deployed two hydrophones from a small rowing boat late at night in flat calm weather. The hydrophone depths were 1 and 2 m, the hydrophones were located vertically one above the other. Two hours of recordings were made.

3. Results

During the recordings with the LPC, in the fish trap and in the spawning bay, sounds were recorded from the herring. The most prominent signal consisted of a series of pulses, where each pulse had a lower frequency emphasis than the previous one (Fig. 2). This sound, we call the pulsed chirp.

In the LPC experiments, 19 out of 20 herrings produced sounds that could be analyzed. The source level of the chirps ranged from 55 to 90 dB re 1 µPa rms (root mean square) at

1 m (73 ± 8 dB, mean ± 1 S.D.; N = 19). The rms intensity was calculated over the length of the signal within the –3 dB points of the signal envelope function. Sounds were first heard at an ambient pressure of 0.2 ± 0.1 bar (N = 19), corresponding to a five-fold increase of the swim bladder air volume.

Each pulsed chirp lasted 0.9–16.2 s (4.2 ± 4.8 s; N = 10) in the LPC experiments, and 32–133 ms (83 ± 28 ms; N = 11) in the field recordings from the spawning bay. Each chirp contained 7–50 (17 ± 13; N = 11) pulses in the field recordings. In the LPC experiments, there were up to hundreds of pulses within a single chirp.

Eleven chirps from the spawning bay were chosen for more detailed measurements of signal properties. The centroid frequency (the frequency splitting the spectra into two halves of equal energy; Au, 1993) ranged from 3.0 to 5.1 kHz (4.1 ± 0.8 kHz; N = 11) for the first pulse of a chirp, and from 2.2 to 4.6 kHz (3.0 ± 0.9 kHz, N = 11) for the last pulse. The mean-square bandwidth (the S.D. of the spectrum; Au, 1993) was 1.2–3.9 kHz (2.4 ± 0.7 kHz; N = 11) for the first pulse, and 1.6–4.9 kHz (2.9 ± 1.0 kHz; N = 11) for the last pulse of the chirp. The interval between pulses ranged from 1.2 to 12.8 ms (5.7 ± 3.1 ms; N = 9) at the start, and from 0.8 to 7.1 ms (4.5 ± 1.9 ms; N = 9) at the end of the chirp.

During the LPC experiments, chirps were only heard when air was emitted from the anal opening of the fish. From visual observations of the video recordings, it was estimated that each bubble detaching from the herring had a radius of about 0.5–1.5 mm. In the herring trap recordings, no bubbles were released from the fish observed with the video camera. The hydrophone inside the trap recorded large amounts of pulsed chirps, whereas these sounds were barely detectable on the hydrophone outside the trap. This made us confident that the sounds were produced inside the trap. During the field recordings, the visibility was not sufficient to observe whether the fish released bubbles or not, but herring was regularly observed to gulp air at the surface.

4. Discussion

4.1. The biological significance of the pulsed chirp

The pulsed chirp (Fig. 2) has previously been observed in recordings of herring (Schwarz and Greer, 1984). To our knowledge, there have been no reports of any other marine animal producing this kind of sound. Eels (*Anguilla anguilla*; J. P, Lagardère, personal communication) and some other fish species (e.g. weakfish, *Cynoscion regalis*; Sprague, 2000; see Fish and Mowbray, 1970 for other examples) are known to produce transient sounds of similar frequency content as the herring pulses, but these sounds do not seem to have the frequency decay between consecutive pulses characteristic for the pulsed chirp. However, some other members of the Clupeid family, such as *Sprattus sprattus* and *Sardina* also have a canal from the swim bladder to the anal opening. Even though recordings of these species are unknown to us, one may predict that they produce sounds similar to herring. The pulsed chirp may serve as a fingerprint to detect and identify Clupeid fish schools by using passive acoustics. The time-band width product (Au, 1993) of the signal is large, in the order of 100–1000, so that they are feasible for automatic detection as well as localization techniques using cross-correlation and matched filtering. As the ratio of the acoustic wavelength and the source size is much larger than one (around 400), we expect the sound to radiate almost omni-directionally around the fish. This also facilitates automated detection.

It is not clear as to why herring release bubbles. If the swim bladder produced gas at depth, this gas would expand as the fish ascends. Instead of absorbing the gas (as most teleosts do), it would be convenient for the herring to release the superfluous gas through the anal opening. However, experiments have shown that the herring swim bladder may not produce any gas (Fahlén 1967, Blaxter and Batty, 1984). If gas only enters the swim bladder through inhalation at the surface, there is no physical reason why gas has to be released during ascent. Also, herring gas release has been observed both by ascending and descending schools (Nøttestad, 1998). In our study, pulsed chirps were heard from fish caught in a trap and in a shallow spawning bay, where ascent and descent was restricted to a few meters. These observations indicate that gas release, rather than being a physical response, is a behavioral response (such as stress or predator avoidance; see Nøttestad, 1998). It has been suggested that the bubble release could be a way for the herring to distract predators, such as killer whales (Nøttestad, 1998; see also Similä and Ugarte, 1993).

It may be inferred from the audiogram of the herring (Enger, 1967) that they can hear the bubble release from other fish at a distance up to around a meter. This is larger than the typical distance between individual fish in a herring school (Radakov, 1973; Domenici et al., 2000). Therefore, the individual herring can probably hear the bubble release from their nearest neighbors within a school. Whether or not these sounds have any meaning for the fish has to await further acoustic and behavioral observations. It is also possible that predators, such as killer whales *(Orcinus orca)* and harbor porpoises *(Phocoena phocoena)* can detect herring from listening to the sounds of schools releasing bubbles. Herring reacts on the echolocation sounds made by killer whales (Wilson and Dill, 2002). Thus, the pulsed chirp may be a cue for the predator to find the school without disclosing its presence with sonar.

4.2. A model for pulsed chirp generation

A possible mechanism for the sound production of the pulsed chirp is air bubble oscillations, which are known to produce sound efficiently under water (Longuet-Higgins, 1989). When small quantities of air are pressed through the anal opening of the fish, pulses could be produced as the external bubble oscillates while attached to the anal opening by surface tension. For every portion of air added, the at-

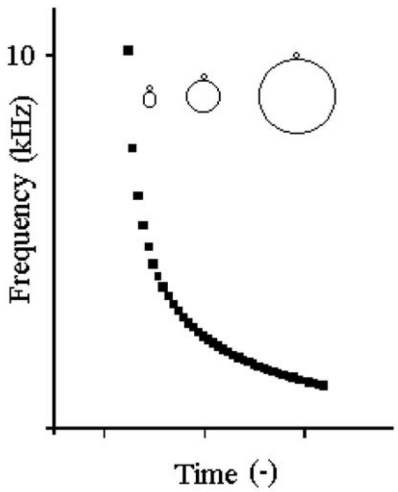

Fig. 3. Visualization of the proposed model of herring chirp generation (for details see text): the air bubble is attached to the anal opening and is filled by air parcels of constant volume from the anal duct. Each air parcel causes the bubble to resonate and thereby produces a pulse. For the consecutive pulse, the bubble has grown, and the frequency emphasis is lower. The expected spectrogram of a pulsed chirp from this model is shown. The time scale is arbitrary.

tached bubble is given an impulse to oscillate and generate sound at its resonance frequency, which is determined by its size and the ambient pressure (Plessett and Prosperetti, 1977). When the attached bubble grows large enough, it will detach and ascend towards the surface.

We propose that the mechanism behind the generation of each chirp is the formation and release of a single bubble from the anal opening. This explains the decay of the centroid frequency throughout the pulses within a chirp, as the resonance frequency of the attached bubble decreases when it gets larger (Plessett and Prosperetti, 1977). In Fig. 3, the spectrogram of a pulsed chirp is depicted, modeled according to the sound production mechanism proposed here. The simulated chirp is similar to the temporal and the frequency structure of a pulsed chirp when a series of air portions of equal volume is added to the bubble. More detailed simultaneous hydrophone and video studies of the sound generation process would clarify whether this sound production model is realistic.

This model may also explain why the frequency content of the pulses varies as a function of the ambient pressure (Fig. 4). The black lines in Fig. 4 show the resonance frequency of air bubbles of radii 0.5 and 1.5 mm as a function of the ambient pressure. The bubble resonance frequencies circumscribe the measured centroid frequency of the last pulse within a chirp, both for the LPC and the spawning bay recordings. This may indicate that the released bubble size is between 0.5 and 1.5 mm radius, which is also what was estimated from visual inspection of the video uptakes from the experiments with the LPC. Fig. 4 predicts that the frequency content of the chirps would increase with depth. Further recordings of herring at different known depths are necessary to test this prediction. The conjecture is corroborated qualitatively by observations from submarines recording herring schools at depths down to 50 m.

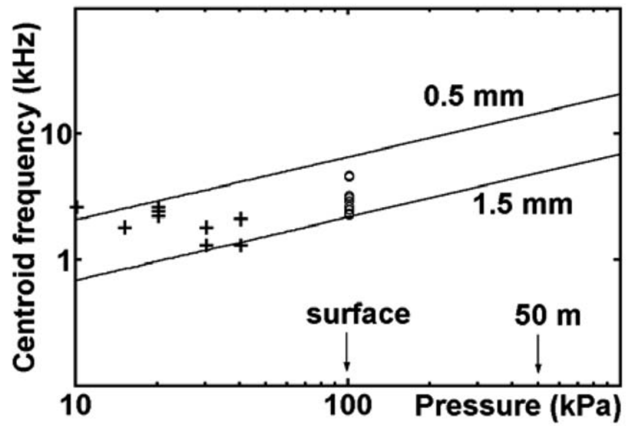

Fig. 4. The centroid frequency of the last pulse of herring chirps and the ambient pressure. '+' data are from LPC experiments, and '*o*' data are from field recordings of spawning herring. The lines correspond to the resonance frequency of air bubbles of radius 0.5 and 1.5 mm. The arrows indicate the ambient pressure at the sea surface and at a depth of 50 m. For details and definitions, see text.

During LPC experiments, sound was only heard while air was released from the anal opening. During the fish trap recordings, no bubble release was observed in synchrony with the recorded pulsed chirps. One reason for this could be that the visibility of the water was limited to a few meters and that the gas release was sporadic in time and space; therefore, fish outside visual detection range may have released the air and produced the sound. Another explanation is that herring may produce sound without releasing air. A possible sound production mechanism in such cases is the internal transportation of air within the alimentary–swim bladder canals.

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