PRELIMINARY INVESTIGATION ON SOUND PRODUCTION BY TWO FISH SPECIES: SPARUS AURATA AND DICENTRARCHUS LABRAX

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1 INTRODUCTION

Fish have evolved a number of ways of producing sound. It is estimated that the families of fish that are capable of producing sound are more than 50, [1]. Despite this fact, it is questionable whether all these fish use sound for some kind of communication. Some may emit sound in response to a particular source of stimulation (i.e. electric) or just by consuming certain types of food. As this latter sound can easily be detected and acted upon by other animals, it is not categorized as a signal or call however, as a part of their particular behavior or in a social context, many fish do produce calls or signals. The nature of this sound varies, depending on the mechanism used to produce them and with most of their energy in the frequency range below 3 kHz.

Sound detected from certain species of fish can be produced in many ways, like clapping together parts of their body or even from active swimming however, the most characteristic sound produced by fish is the sound which emanates from the movements of the swimbladder. There are located specialized striated muscles that compress the swimbladder. These muscles may overlie the swimbladder, or they may be attached partly or wholly to the organ. There are substantial differences in the shape and structure of these sonic muscles in individual species.

Differences may also even exist between the sexes, the male usually having more developed muscles or the female not producing sound at all. These pairs of specialized muscles can contract very rapidly. For example, the sonic muscle of the oyster toadfish, is considered the fastest vertebrate striated muscle, [2]. Sonic muscles can also have very good synchronization, although there are fish which demonstrate alternate muscle contraction, [3]. If they are stimulated repeatedly, they contract at a very fast rate. A single synchronous contraction of the paired muscles, results in a pulse of sound or even a knock or brief thump. In a repeated contraction, individual pulses are produced and detected, resulting in a longer call. If the individual pulses are close to one another they result in a grunt, a series of rapidly repeated pulses which can reach a rate of 100 pulses per second in some fish. In the case of the Lythe (Pollachius pollachius), for example, the rate of production is in the order of 100 per second. It should however be noted that not all soniferous fish can produce grunts. These specialized sonic muscles exist in unrelated fish families but can also be absent among closely related species. This fact suggests that the sound producing muscular mechanism has evolved independently in different fish, [4].

It is a subject of ongoing research as to whether the two fish species, Sparus aurata (Gilthead seabream) and Dicentrarchus labrax (European seabass), are capable of producing sounds via any of the teleost fish known mechanisms. In this study, the spontaneous sound production of these two species is investigated at a preliminary level with a view to the development of future projects.

2 ESTIMATION OF SWIMBLADDER RESONANCE FREQUENCY

The swimbladder is involved in sound production for many types of fish and therefore its role is very significant. A large body of water needs to be moved for a relatively low frequency sound to be generated efficiently. This is achieved by changing the volume of the swimbladder through the contraction of the surrounding muscles, [3].
The structure of the swimbladder itself is what makes it resonant. The effect of swimbladder tissue and surrounding muscle on the resonance frequency, as expressed through the swimbladder surface tension and surrounding muscle mass, is minimal. The surrounding muscle and swimbladder tissue are responsible mostly for the dissipation mechanism. As a result, the oscillations die out fast, mainly because of the large amount of water that has to be moved. So the sound produced has a short duration, it is pulse like, and the frequency content of this pulse covers a range that is usually centered around the resonant frequency. So, longer calls are usually produced by repeated muscle contractions. The acoustic modelling of the fish swimbladder is mainly of interest to the fields related with the detection of fish schools, with the quantification of fish by means of acoustics and with the hearing and sound production mechanisms in fish.
The swimbladder in many fish species has an elongated shape with an irregular surface and is usually modelled as an air filled inclusion in water (bubble). We can say that the shape of an oblate spheroid best approximates the shape of the swimbladder. The family of equations in Cartesian coordinates that represent the spheroids are,

$$\frac{x^2}{a^2}+\frac{y^2}{e^2a^2}+\frac{z^2}{e^2a^2}=1 \tag{1}$$

where 2α is the axis of revolution and e is the ratio of major to minor axis. The resonance frequency can be estimated theoretically considering spherical or prolate spheroid cavities, and also through theoretical calculations of scattering from these shapes, [5, 6, 7, 8, 9, 10]. Results confirm that resonance frequency of the bubble increases when it is deformed from the spherical shape, as is the case of a prolate spheroid, [7]. Considering spheroids with various values of e's, (e being the ratios of major to minor axis), and all having the same volumes relative to a sphere, their resonant frequencies have a slight dependence on e, [5]. As the ratio e reaches high values, the ratio of the prolate spheroid resonant frequency to spherical resonant frequency, tends to $e^{1/6}\left(2/\pi\right)^{1/2}$. In other cases, i.e. when e=3, the resonance frequency of an oblate spheroid is only 5 percent higher than that of a sphere with the same volume.
As a first approximation, we may consider that the swimbladder behaves like a gas bubble of the same volume, and that it is surrounded by water. Such a monopole is omnidirectional and behaves almost like an underwater bubble, for which certain physical characteristics can be obtained, [11].
This kind of model has been used as a primary tool in cases where one wants to find how the swimbladder responds to acoustic waves emitted from a certain source. Many studies have looked at the problem of acoustic scattering from fish and have used several models for that purpose, [9, 10, 12].

When the bubble is undisturbed, the air pressure in the bubble is constant and that pressure equals the ambient pressure of water. Changes in the volume of the bubble (the swimbladder) will affect the pressure in the cavity according to Boyle's law. If the temperature of the air does not vary much, the volume is inversely proportional to the pressure. The whole system, swimbladder plus the inertia of the surrounding medium, behaves like a spring-mass system. The spring like property of the swimbladder comes from the compressibility of the enclosed air and the mass like property comes mainly from the surrounding water. An external force could be such as an acoustic wave or a muscle twitch. If the frequency content of that acoustic wave is strong in the region of the swimbladder resonance frequency, the motion of this bubble will be the greatest, and the radiated acoustic waves will be stronger than at other frequencies.

It is also logical from surely a physics point of view, to assume that for fish sound production to be efficient, the frequency content of the pulsating swimbladder has to be centered around the swimbladder's resonance. The estimated resonance frequency related to a spherical gas bubble in water, [5,13], is given by,

$$f_r = \frac{1}{2\pi R_o}\sqrt{\frac{3\gamma P_o}{\rho}} \qquad (2)$$

where γ is the ratio of specific heats for the gas in the bubble (around 1.4 in our case), P_0 is the ambient pressure, p is the density of the medium and R_0 is the bubble radius. We need to make an estimate of the bubble radius, as applied to fish. A typical estimate will be that R_0 is 5% of the total fish length. Considering a 25 cm fish near the surface (P_0 is 1 atmosphere), equation (2) gives a frequency of 257 Hz. Based on this relation, a graph of swimbladder resonance frequency with respect to the fish length is plotted in figure 1 (solid curve).

There are also experimental investigations on the relation between the swimbladder resonance frequency and the length of fish, using sound scattering experiments, [14]. Since the resonance frequency changes with depth, in those fish that can maintain the swimbladder volume by adapting the amount of air, the radius should remain constant, while the resonant frequency should vary as $P_0^{1/2}$, P_0 being the ambient pressure. For non adapting fish the law is $P_0^{5/6}$.
Using these scaling laws, for several species adapted to surface pressure, the resonance frequency obeys the following empirical formula,

$$f_r = K / L \qquad (3)$$

where L is the fish length in meters and K a constant, its value deduced from scattering experiments for this relation to give satisfactory predictions, [14]. The value of K is related to the percentage of the swimbladder length to the fish length (and also to the swimbladder radius). Since there is no data for the two species under consideration and since these percentages are 26% and 42% for cod and herring respectively and the mean percentage for *Sparus Aurata* is 34%, we have picked a typical intermediate value of 120 for K, considering that K has the value of 170 for herring and 80 for cod, [14]. Then, based on this relationship (3), a graph of swimbladder resonance frequency with respect to fish length was plotted in figure 1, (broken curve). Both curves of fig. 1 came from simplified swimbladder models. Since at this point in time there are not accurate swimbladder shape measurements and experimental data on the swimbladder resonance frequency, the approach explained above is mainly used to support the notion of swimbladder originated sound generation mechanism for the two studied species.

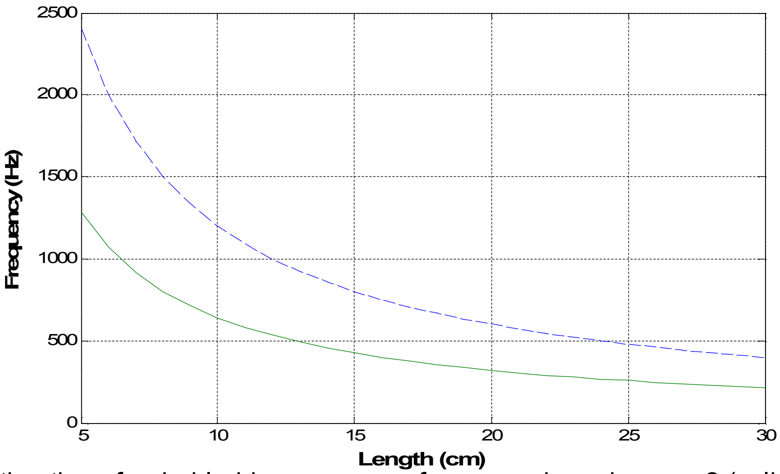

Figure 1: Estimation of swimbladder resonance frequency based on eq. 2 (solid curve) and eq.3 (broken curve).

3 MATERIALS AND METHODS - RESULTS

We will report on two main groups of recordings (Group A and Group B). Recording of group A, took place at the Institute of Aquaculture laboratories of the HCMR (Hellenic Center of Marine Research), on the island of Crete, Greece. Since, to our knowledge, there was no prior research done on sound production of these two species, recordings were carried out in more than 3 different concrete and plastic tanks with running water, each housing different populations of 40 specimens. Tank dimensions were 3 x 2 m and 1.5 m deep and water temperature was 18-21 ^{o}C. All recordings took place during daylight hours, between 10:00 am – 14:00 p.m., during the months of March and July. Even with the termination of the vigorous water supply, the background noise in the tanks was high because of the structural transmitted sound from nearby tanks. Also, there was no capabiblity to turn off the water drainage system, so the recording time period (without water supply) was limited to about 10 minutes. In these tanks were performed four series of recordings in total on different days. Two involving *Sparus Aurata* (one supplied from a breeders population), fish length 25.0 ± 1.5 cm, and two involving *Dicentrarchus Labrax,* fish length 15.0 ± 1.0 cm. A fifth recording in this group was done in a 30 litre dark plastic bucket with 20 fish (*Sparus Aurata),* of length 11.0 ± 1.0 cm.

In the cases reported here, two channel recordings were simultaneously performed in each tank using two hydrophones placed about 1.8 m apart. The signal from one of the hydrophones (an omni hydrophone, Reson, TC4013) was recorded via computer through a conditional amplifier (Reson CCA-1000) and a portable data acquisition board (Waveport P16). The other hydrophone signal (Aquarian Audio, H2-6), was recorded directly into another portable computer. Sampling rates used were mostly 22050 and 48000 Hz.

The processing of the recorded sound files usually consisted of several steps. For each identified sound, a separate sound file was created and high pass filtered (70-80 Hz cutoff frequency) to remove interference noise from nearby generators. Then, each file was denoised. The denoising method used in Group A recordings was spectral subtraction. Since we did not want its known 'musical tone' artefact to interfere with any of the fish sounds, this method for recording Group B was replaced by a better algorithm which utilizes a minimum mean-squared error of the log-spectra estimator, [15]. The effect of denoising and band pass filtering on a particular sound file is depicted at Fig. 4.

Each sound file created in this way contained one or more individual pulses or (in a few cases) pulsetrains, as will be discussed below. The total recording time in this group was about 2.5 hours. From the 4 initial recordings in the tanks 51 sounds were isolated, 32 of *Sparus Aurata (20* of which came from *Sparus Aurata* breeders), and 19 of *Dicentrarchus Labrax.* All of these sounds appeared as isolated sounds.

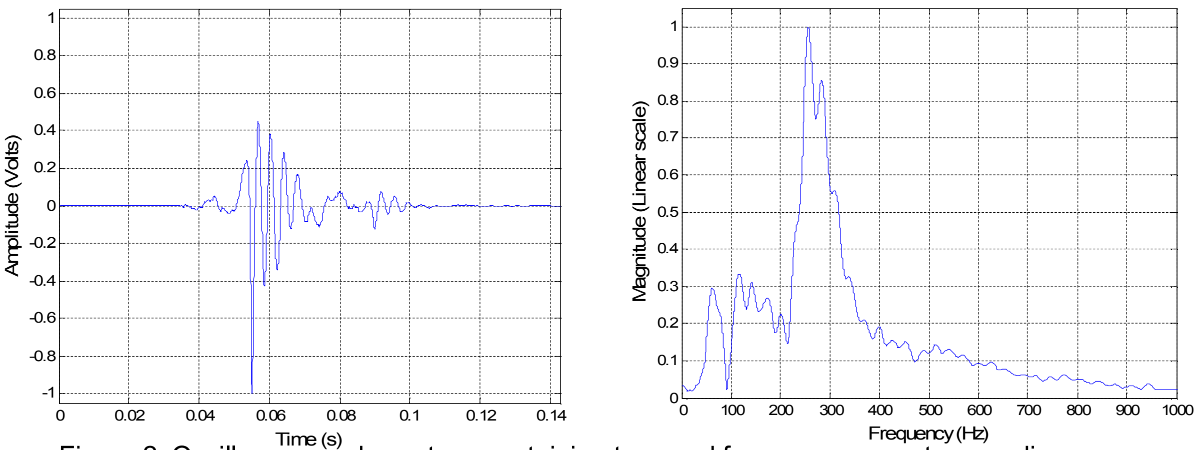

Figure 2: Oscillogram and spectrum pertaining to sound from sparus aurata recording.

A few (4-5) pertained to fish sounds, deduced by examination and comparison of their oscillograms with swimbladder sound signatures published from other species [16, 17]. The energy of all these sounds was within 200-300 Hz.
The waveforms for the rest of the sounds found were either not typical of a swimbladder produced waveform, (exhibiting few rapidly attenuated cycles), or they were weak and not so well defined due to the possibly large distance from the hydrophone in conjunction with the background noise.
There were also cases where the nature of the sound or the production mechanism could not be easily identified, attributed in some cases to hydrodynamic sound produced by very active fish swimming close to the hydrophone. The energy of all these sounds was within the range 600-800 Hz or 2500-3000 Hz. Possible justification of sound produced at the higher frequency range, could be based on an interacting muscle (vibrating at its own eigen-frequency) and swimbladder model.
A typical swimbladder produced sound waveform, along with its spectrum, is shown in Figure 2. We notice the spectrum peak around 258 Hz, exactly around the region predicted by the swimbladder model discussed previously and expressed through equation (2), and the solid curve of Figure 1 for a fish length of 25 cm. This short duration waveform, termed a knock, is typical of fish sounds produced via the swimbladder [16, 17], although any repetitive scheme of this kind of waveform was not recorded in any one of the four recordings in this group.
On the contrary, during the fifth recording session performed in the 30 litre bucket, 13 sounds generated by *Sparus Aurata* were found, 3 of which came in the form of pulse-trains. The sonogram of one of these sounds is pictured in Figure 3. The FFT analysis of this sound as a whole and from the analysis of the individual pulses, showed most of the signal energy is in the range of 500-600 Hz. For fish lengths of 10, 11 and 12 cm, the frequencies based on equation (1) are respectively 643, 584 and 535 Hz. Comments on the pulse-train patterns will be given when discussing the sounds of the second recording group (Group B).

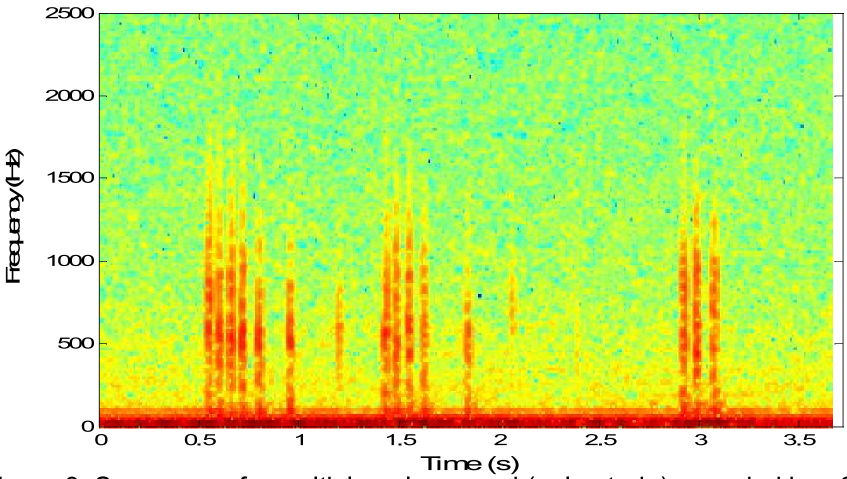

Figure 3: Sonogram of a multiple pulse sound (pulse-train) recorded in a 30 litre container.

Recording Group B came about as a necessary step to obtain higher level sound signals and better S/N ratio. They were performed in two 1.3 litre fiberglass aquariums (114x35x33 cm^3), placed in a quiet temperature controlled and lit room. Each aquarium housed 15 specimen of Sparus Aurata and Dicentrarchus Labrax. Mean values of specimen lengths were 14.5 ± 1.0 and 15.0 ± 1.0 cm, respectively. Recordings were made on six different days during the month of November and on each day approximately 3 hours of recordings were made at different daylight times. No recording sessions were performed at night hours. From the total data set, 204 samples of Sparus Aurata and 32 sound files of Dicentrarchus Labrax were singled out, each one containing one or more sounds or pulse-trains. The number of Dicentrarchus Labrax sounds were much less than Sparus Aurata sounds because for some unspecified reason they passed away after the second day of recordings. In this recording group (Group B) 19 pulse-train sounds, all coming from Sparus Aurata were identified.

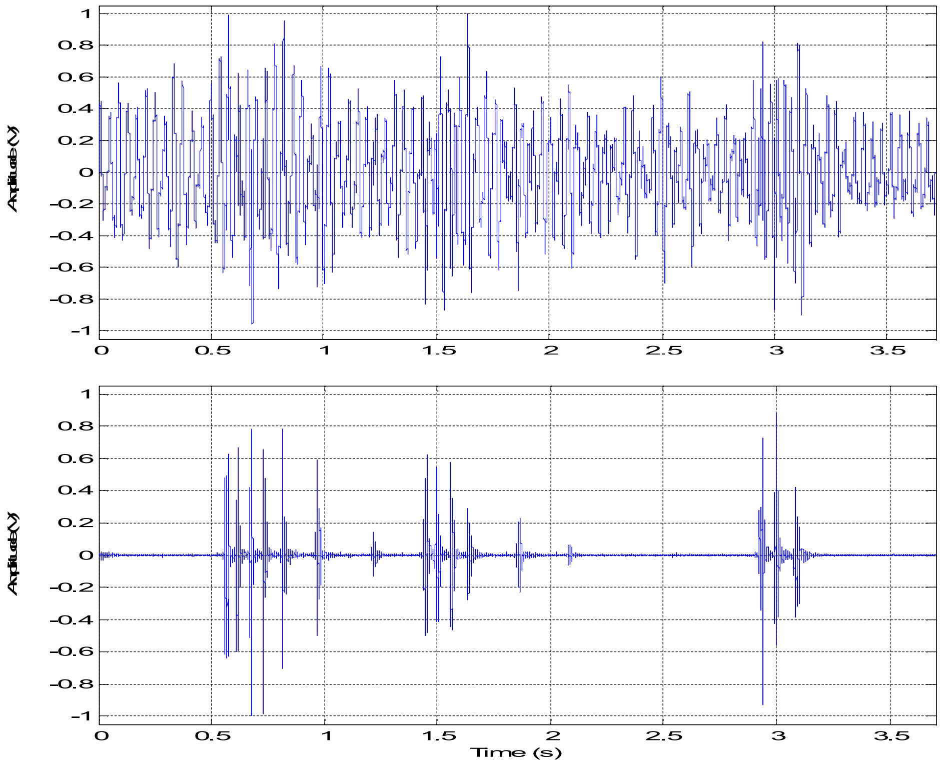

Figure 4: The original waveform of figure 3 and its denoised version after bandpass filtering at 270-1500 Hz.

Figure 5 pictures the sonogram of the longest pulse-train found, consisting of more than 55 individual pulses. This pulse-train is made up of an uninterrupted sequence of pulses. Little variation in repetition pulse period was observed. For the time interval between 4.583s – 16.330s, the mean value of repetition period of the pulses is 329.5 ms (s.d. 84 ms), corresponding to a repetition rate of 3 pulses per second.

Most of the individual pulses, in this sequence, had a majority of their energy in the region around 760 Hz with some energy between 3600-3800 Hz. Note that there are a few pulses (two in the begining of the file at 1.350s) and one towards the end (at 23.600s) having their energy only in the region of 3500 Hz.

A pulse-train, was defined as a sequence made up of 3 or more pulses. All the pulse-trains identified consisted of 3 to 5 individual pulses. We should also note here, that cases with two pulses appearing close to one another (resulting in a twin pulse or dual knock), were not found. On the contrary, there were a few cases where a pulse-train of 3 to 5 pulses was followed by another pulse-train after a quiet time interval which was more than 8 times the interpulse interval. In general, the mean value of pulses in a pulse-train was 4 (if we single out only one case that reached the value of 55).
In all the different sequences detected and established as pulse-trains, the observed pulse repetition rates varied only slightly. Out of 15 pulse-trains, 12 are in the range from 4.0 to 6.4 Hz, with mean value of 5.5 Hz (s.d. 0.7 Hz). This could be a parameter characteristic of the *Sparus Aurata* species. Table 1 shows the number of pulses in a pulse-train, the repetition period of pulses in a pulse-train, the repetition rate of pulses in a pulse-train and the frequency of dominant acoustic energy. The acoustic energy of the pulses in pulse-trains had most of their acoustic energy in the neighbourhood of 786 Hz (s.d. 71) which is in accordance with the broken curve of figure 1, based on relation (2) which for a fish length of 14.5 cm suggests a resonance frequency of 827 Hz. In general, all pulse sounds found (isolated or in a pulse-train) for both examined species, present their peak acoustic energy in the same region, although there were cases where strong acoustic energy (usually -8 to -18 dB from the lower frequency dominant peak), also appears in higher frequency regions usually between 3600 to 3800 Hz and/or at 5900 to 6300 Hz. Comments on the production mechanisms or the justification of strong energy content in these frequency ranges are given in the discussion below.

No. of pulses in pulse-train	4 ± 1	S.D.
Repetition period of pulses in pulse-train (ms)	180	27
Repetition rate of pulses in pulse-train (pulses/second)	5.5	0.7
Frequency of dominant acoustic energy (Hz)	786	71

Table 1: Main parameters of *Sparus Aurata* pulse-train calls produced under voluntary conditions.

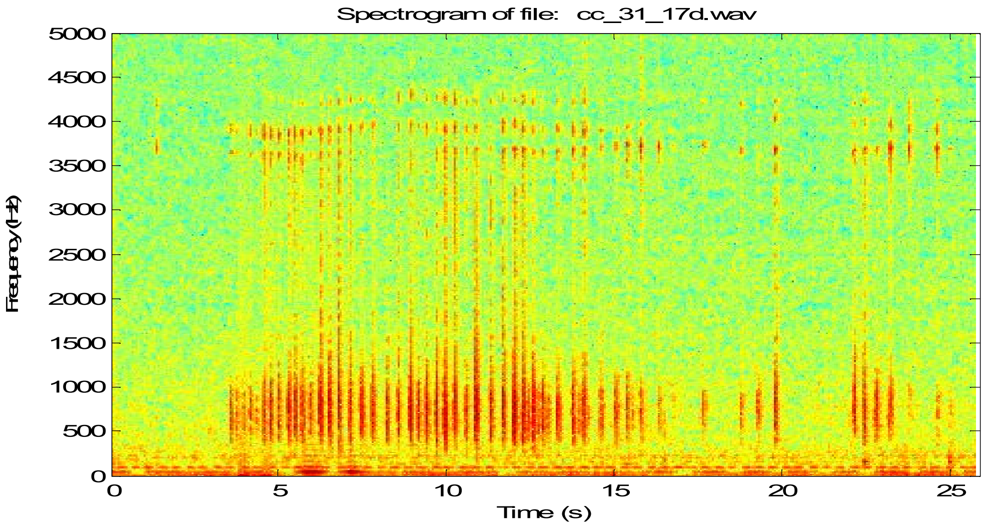

Figure 5: Sonogram of the largest pulse-train recorded (recording group B).

In all analyzed sounds, a regular pattern concerning the waveform envelope or the number of cycles in each pulse could not be established. The accurate counting of cycles in every pulse becomes difficult because pulses die out fast and also have varying levels with respect to background noise. Nevertheless, by examining the individual pulses forming the pulse-trains, we could say that in most of the cases pulses were made up of 3-4 cycles, although in four cases pulses had more than 15 cycles. This observation stands for all typical single knocks found. A well defined typical knock sound consisted of 3 to 6 cycles. In cases where a pulse consisted of more than 20 cycles, the waveform envelope had a form similar to a dying out beat pattern.

Based on the sounds from recording Group B which involved fish of the same size, the following general remarks can be made:
The duration of the pulses varied widely, ranging from 4.5 to 70 ms or more. The number of cycles in each pulse ranges from at least 3-4 up to a few dozen in some cases, the most typical case being 5-10. All the sounds recorded can be put in three categories based on the frequency region containing most of the signals acoustic energy. In the first category, pulses have their energy only in the region of 500-1000 Hz. In the second category, pulses have their energy both in 500-1000 and 3600-3800 Hz and in the third category they have their energy only in 3600-3800 Hz, although the number of recordings in this category is small (about 15). Pulses at times appear in a sequence forming a pulse-train. From 19 sequences found, 15 were classified definitely as pulse-trains with their main describing parameters appearing in Table 1.
Although findings are of only a preliminary nature and are at times supported by educated guess-work, it is reasonable to conclude that the two fish families (*Sparidae* and *Moronidae*) thought to be non-soniferous by researchers have at least one species each (*Sparus Aurata* and Dicentrarchus Labrax) which are sound producers, the swimbladder being their main sound production mechanism.

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