Broadband acoustic classification of individual zooplankton and fish: A review of recent work

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Abstract

Echoes resulting from broadband insonification of marine life such as zooplankton and fish are rich with information. The challenge lies in developing an optimal approach toward extracting meaningful biological information from the data. Because of the complexity of the acoustic scattering by the organisms, we have studied the scattering through a combination of theoretical modeling and extensive laboratory measurements of broadband acoustic scattering by a variety of live individual animals. Specifically, we have recorded echoes from three major anatomical groups of zooplankton: 1) fluid-like (shrimp and euphausiids), 2) elastic shelled (pteropods and (benthic) periwinkles), and 3) gas-bearing (siphonophores), as well as a bladder-bearing fish species (alewife). The frequencies were continuously distributed over about an octave of bandwidth: 350 - 650 kHz for the zooplankton and 40 - 100 kHz for the fish. Some of the animals were rotated over all angles of orientation in one or two planes and in one-degree steps. The echoes were examined in both the frequency and time domains. In the time domain, pulse-compression processing was applied in order to resolve individual features of the animals. The data were classified using both physics-based and statistics-based algorithms. Size, gross anatomical group, and sometimes orientation information could be inferred from the data.

1. Introduction

The acoustic scattering characteristics of marine life are a complex function of size, shape, orientation, and material properties of the animals as well as a function of the frequency of the acoustic signal (Figure 1). Given these many dependencies, there are ambiguities in interpretation of the data. One method of reducing the ambiguities involves increasing the spectral coverage of the acoustic signals, hence increasing the amount of information contained in the echoes. Unfortunately, most systems are narrowband (i.e., bandwidths that are roughly 10% or less of the carrier frequency) and at best contain several narrowband transducers to increase spectral coverage.

Broadband transducers can represent a significant improvement over multiple discrete-frequency transducers because they permit continuous coverage of the frequency spectrum. Given the engineering challenges associated with the design of such systems, there are few such transducers available in the commercial market. However, the number of these systems continues to grow and the possibility of routine use of broadband systems for zooplankton and fish biomass field surveys is increasing.

Our research program involves investigating the broadband acoustic backscattering characteristics of live individual zooplankton and fish. A major component of the work involves making measurements of the scattering in a laboratory tank under controlled conditions. The purpose of the research is two-fold: 1) to use the broadband data as a basis for developing or improving models of acoustic backscattering and 2) to develop new approaches for acoustic classification of the animals in field surveys. The work has spanned a variety of animals including three major anatomical groups of zooplankton (fluid-like, elastic shelled, and gas-bearing) as well as swimbladder-bearing fish.

In this paper, we review the approaches and results from our broadband scattering measurements of the various animals and the resultant broadband classification methods. The various methods are compared with each other as well as discussed in the context of eventual use in field surveys.

2. Broadband Backscattering Measurements and Signal Processing

Measurements of acoustic scattering have been made on live individual zooplankton and fish in tanks both on land and on the deck of a ship at sea (see, for example, [1-6]). The acoustic frequencies have ranged from 24 kHz to 1.4 MHz and some of the transducers have been used to transmit broadband chirp signals with about one octave of bandwidth (Figure 2). In some of the measurements, the orientation dependence of the scattering has been studied. The animals were rotated over the full range of 0-360° in 1° increments during a ping sequence [4-6]. The rotations were done in two planes of the animal body. The measurements were conducted with two closely spaced transducers, one for transmission and one for reception. Calibration was performed by separating the transducers so that they were facing each other and recording the transmission in the absence of any animal.

The chirp signals have been examined both in the spectral and temporal domains. In the spectral domain, the Fourier transform of the backscattered signal was calculated and normalized by the transform of the calibration signal. Once certain geometric factors are included, the result is target strength versus frequency.

In the temporal domain, the signal was temporally compressed by cross correlating the received signal with the calibration signal. For an "ideal" scatterer whose frequency response is uniform with frequency, this pulse compression approach would be identical to a matched filter. The matched filter output consists of a relatively narrow single peak with small side lobes (Figure 2).

Both the spectral and pulse-compressed temporal signals provide information on the scattering characteristics of the animals.

3. Scattering Physics

Because of the great complexities and the large number of species present in the ocean, the animals have been categorized according to their gross anatomical properties (Figure 1). Acoustically, there are three main groups of zooplankton: 1) fluid-like (e.g., shrimp or euphausiids) where the animal body does not support a shear wave and the material properties are very close to that of the surrounding water, 2) elastic shelled (e.g., pteropods) where the outer shell dominates the scattering, and 3) gas-bearing (e.g., siphonophores) where the gas inclusion will contribute significantly to the scattering. For fish, there is scattering from various components of the anatomy including the swimbladder (when present) and skull. Given the great strength of the echo from the swimbladder, the fish can be categorized according to whether or not there is a swimbladder.

Along with the diversity of classes of scattering mechanisms is a corresponding diverse set of scattering models. Reviews of those models can be found in other texts [2, 7-11].

4. Classification

4.1 General

Because of the diversity of scattering mechanisms, the corresponding difference in the scattering "signature" of the animals can be used for classification purposes. The challenges in developing a classification approach lie in:

1) Developing an adequate understanding of the various scattering signatures. The understanding must be achieved through both modeling and experimentation.

2) Developing an acoustical system with sufficient bandwidth so that the signatures can be adequately observed.

3) For a given acoustical system and associated processing algorithm, identifying the degree of overlap between signatures from the various types of animals. The degree of overlap is related to the uniqueness of the classification result. The less the overlap, the greater the success of the classification.

There are various approaches for classifying the data in terms of meaningful biological parameters. The approaches can be divided into two broad categories involving the spectral and temporal domains. Although each approach is directly connected to the same scattering physics, each has advantages specific to different applications.

4.2 Classification with Spectral Information

Generally, the frequency spectra of broadband echoes from different types of scatterers will have different characteristics (Figure 3). This is due to the fact that echoes from the different scattering features of the animals will interfere in a manner specific to the anatomy of the animals, and that interference pattern is dependent upon frequency (Figure 1).

Classification of the spectra can be approached either through a model-based approach where the scattering physics is incorporated into the classification scheme or a statistics-based approach where the classification relies on empirically-derived information. One model-based formulation involves the covariance-based approach where the observed spectra are compared with previously modeled echo spectra of known species. The classification is based on maximum correlation between the spectra. The method involves calculation of the Covariance Mean Variance metric:

$$C^{(p)} = K^{(p)} \cdot X^{(p)} \cdot U^{(p)} \quad (1)$$

where p is the class of the animal, X is the mean similarity matrix, and U is the variance similarity matrix [12].

The symbol K represents the covariance between the observed data matrix D and the modeled space matrix M and is given by

$$K^{(p)} = D^T M^{(p)} \tag{2}$$

Each column of D contains a mean-subtracted energy-normalized observed echo spectrum and each column of M contains a mean-subtracted energy-normalized modeled realization for class p. Although this approach was implemented with a model, the mathematical framework was general enough so that measured spectra could be used in place of modeled.

4.3 Classification with Temporal Information

The different scattering features of the animals, such as front and back interfaces, will each have an associated echo that arrives at the acoustic receiver at a different time. The differences in time of arrival and relative strength of the echoes can be used for classification. With conventional gated sine wave (i.e., narrowband) transmitted signals, these different scattering highlights normally cannot be resolved, preventing the possibility of classification of the highlights. However, with a broadband chirp signal, the received signal can be processed in such a way that the echo is compressed in time. One approach to compressing the received signal involves a cross correlation of the echo $v_r^{(s)}(t)$ with the calibration signal $v_r^{(cal)}(t)$:

$$CP(t) = k_{CP} v_r^{(s)}(t) \otimes v_r^{(cal)}(t). \tag{3}$$

The calibration signal corresponds to the scattering by an "ideal" target with a uniform frequency response. $CP(t)$ is the compressed pulse signal, the symbol $\otimes$ denotes the correlation operation, and k_{CP} is a normalization constant of the correlation process [1, 13]. This pulse compression method is used widely in sonar and radar applications and has the advantage of producing a processed signal with a duration inversely proportional to its bandwidth. For a broadband chirp signal, the duration of the processed signal is typically much shorter than that of the original signal, hence greatly improving temporal resolution. The calibration signal in this case can be obtained when the transmit transducer and receive transducer are separated so that they are facing each other in the absence of a scatterer. When one transducer is used to serve as both transmitter and receiver then the calibration signal can be obtained by reflecting the sound off of an ideal reflector (i.e., one with a uniform frequency response) such as a smooth air-water interface.

The received echo time series $v_r^{(s)}(t)$ due to a scatterer is related to the convolution of the calibration signal (which contains system response) and scattering amplitude of the scatterer. For scatterers such as zooplankton and fish, the compressed pulse output may contain multiple main lobes associated with the different scattering features (Figure 3). The occurrence of multiple main lobes is in sharp contrast to a matched filter output (corresponding to an "ideal" scatterer) that contains a single main lobe. These deviations from the idealized matched filter case contains information from which one can classify.

5. Examples

Both spectral and temporal methods have been used to infer quantities such as animal type, size, and orientation. Although both classes of methods are directly related to the physics of the scattering process, there may be conditions under which one approach has an advantage over another. For example, when sizing the animals, the information may sometimes be more readily obtainable through examining separation between nulls in the spectral pattern as opposed to separation between peaks in the compressed pulse output.

We have made great progress in recent years in the classification of live individual zooplankton with broadband signals [3, 5, 12-15], and very recently with live individual fish [6]. Following are examples:

1) *Classification according to anatomical group.* In the spectral domain, both scattering-model-based and empirical-based approaches have taken advantage of data such as that presented in Figure 3 and using Equation (1) (Table 1). The results indicate the great ability to distinguish between fluid-like, elastic-shelled, and gas-bearing animals. There was enough overlap between scattering signatures to impose the need for scattering models that were more sophisticated when model-based approaches were used.

There is strong evidence that anatomical groups can also be inferred through use of pulse compression. For example, in [13], the variance in separation between peaks in the CP output were related to anatomical group.

2) *Classification according to size.* By calculating the statistical behavior of the separation between the peaks of the CP output, diameter and length of fluid-like and shelled animals have been inferred (Figure 4) [5]. The mode of the histogram for a shrimp was shown to correspond directly with the diameter of the animal, while the maximum value near the end of the tail of the histogram corresponded with the length. Size has also been acoustically inferred through examination of the separation between the nulls in the spectral pattern, which are, in turn, related to the size [16].

3) *Classification according to orientation.* Through use of Equation (1), spectral data from animals of known orientation have been correlated with data from animals of unknown orientation [3]. Given the variability in information, the data can, as a minimum, be used to infer domains of orientation such as whether the animal is near broadside incidence or well off broadside incidence. In the temporal domain, the CP output has provided information regarding the orientation of fish [6]. For fish where both the swimbladder and skull contribute significantly to the echo, the separation between the echoes from the two indicate the range of orientation (i.e., near broadside or well off broadside incidence) (Figure 3).

6. Individuals Versus Aggregations

The research presented herein is focused on classification of animals that are spatially resolved with a broadband acoustic system. Clearly, the results do not apply directly to cases in which the echoes overlap. In order to ensure that animals are resolved in field surveys, it may be necessary to mount the broadband system on an undulating platform whose trajectory involves a wide range of depths so as to reduce the distance between the animals and acoustic system. In the cases in which most echoes are overlapping, then other classification methods must be used. Even in this case, it is still quite advantageous to understand the physics of the scattering process as outlined above. By understanding the physics, then the classification process can be better constrained. For examples of classifying aggregations of animals whose (broadband) echoes overlap, the reader is referred to [17] and [18].

7. Conclusions

Much progress has been made toward acoustically classifying resolved echoes from animals through the use of broadband sonar systems and classification analysis techniques. It is clear from the results that there is a tremendous advantage in the use of broadband systems because of the significant gain in information over that of single frequency or even multiple single-frequency systems. All of our progress to date has involved development of analytical methods based on laboratory experiments. As broadband systems become available for use in field surveys, these approaches can then provide a basis for interpreting the broadband field survey data.

8. Acknowledgements

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Animal Type	% CORRECT (based on max S)			% CORRECT (based on max C)		
	ISC	PSC	BPC	ISC	PSC	BPC
Elastic Shelled (*Limacina retroversa*; #93-29)	100%	100%	96%	96%	100%	12%
Fluid-like (*Meganyctiphanes norvegica*; #93-33e)	40%	64%	76%	68%	100%	84%
Gas-bearing (*Agalma okeni*; #93-18)	100%	100%	100%	96%	100%	32%
Overall	80%	88%	91%	77%	100%	43%

Table 1. Comparative performance of model-based Covariance Mean Variance Classification (CMVC) techniques for three anatomical groups using broadband echo data. The approach includes an Integrated Score Classifier (ISC), Pairwise Score Classifier (PSC) and Bayesian Probability Classifier (BPC). Max S results are those based on assigning observations to the class with maximum score; Max C results are those based on assigning echoes to the class containing the best match model realization. Details from these results and others can be found in [3, 12] and [15].

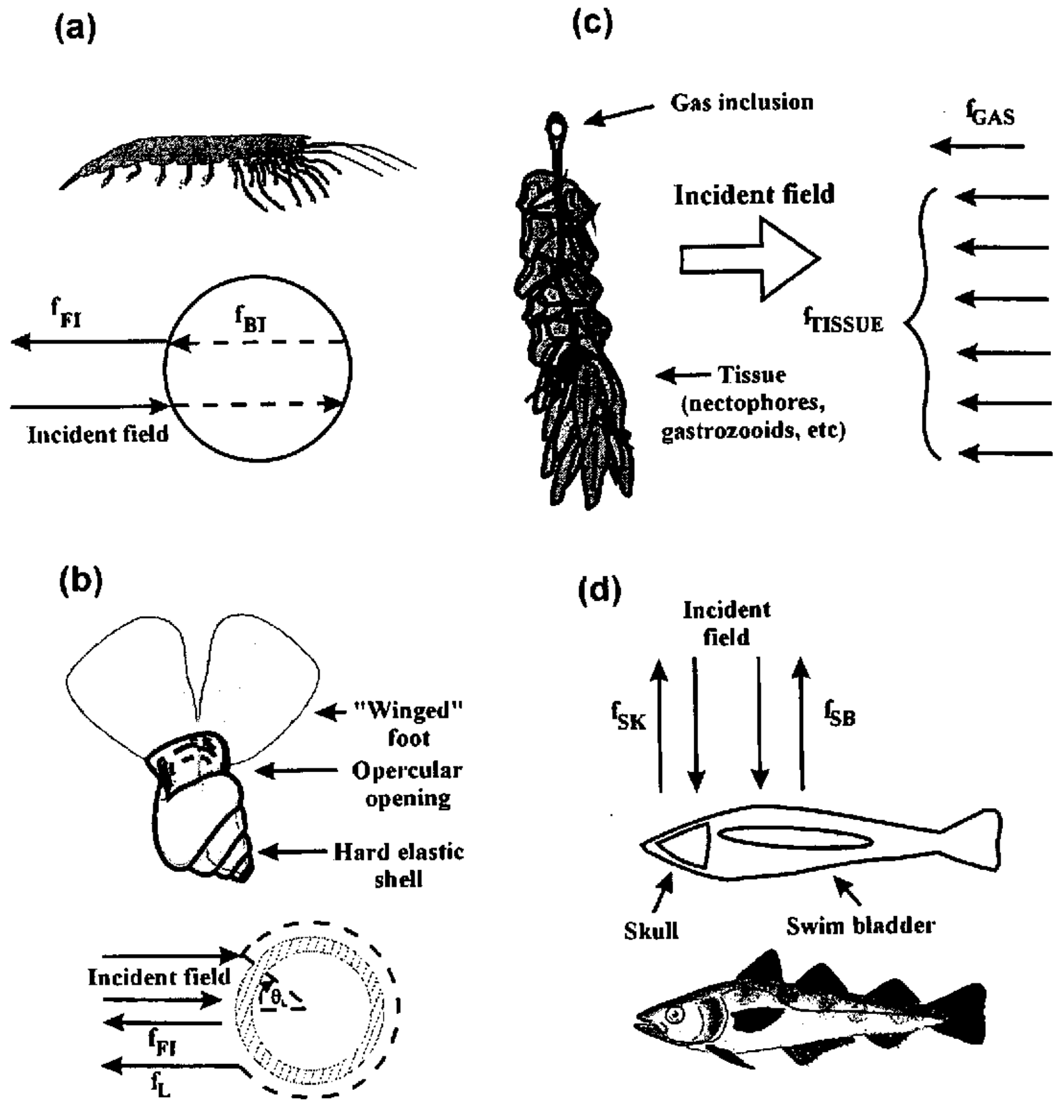

Figure 1. Several anatomical groups of zooplankton and fish and certain important scattering components: (a) fluid-like, (b) elastic shelled, (c) gas-bearing zooplankton, and (d) gas-bearing (swimbladder) fish. The scattering amplitude from the various anatomical features is indicated by an $f_{(\ldots)}$. Adapted from [2].

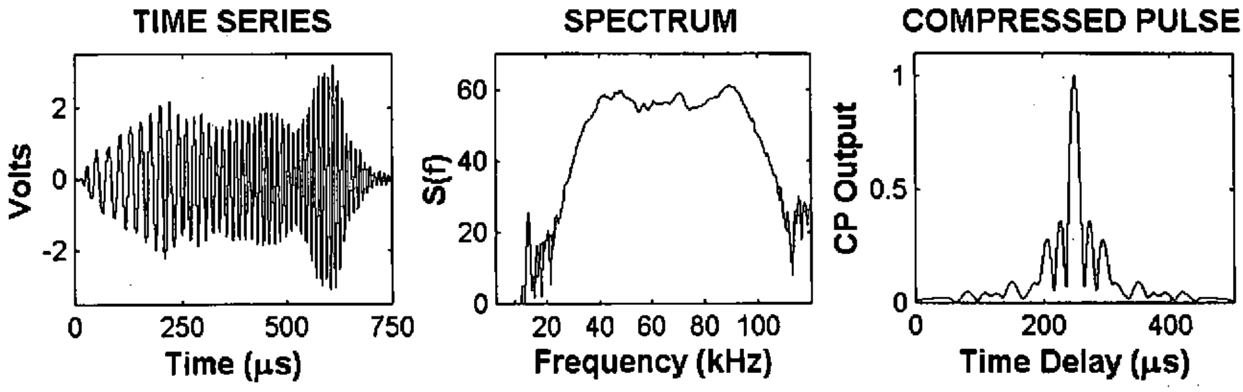

Figure 2. Broadband chirp signal in raw and processed forms: (left panel) time series of calibration signal or equivalently, echo from ideal reflector; (middle panel) frequency spectrum; (right panel) autocorrelation function of the time series in the left panel which corresponds to matched filter output. The width (and hence resolution) of the peak of the autocorrelation is inversely proportional to the bandwidth of the signal. The time delay in the right panel is arbitrary for this calibration signal.

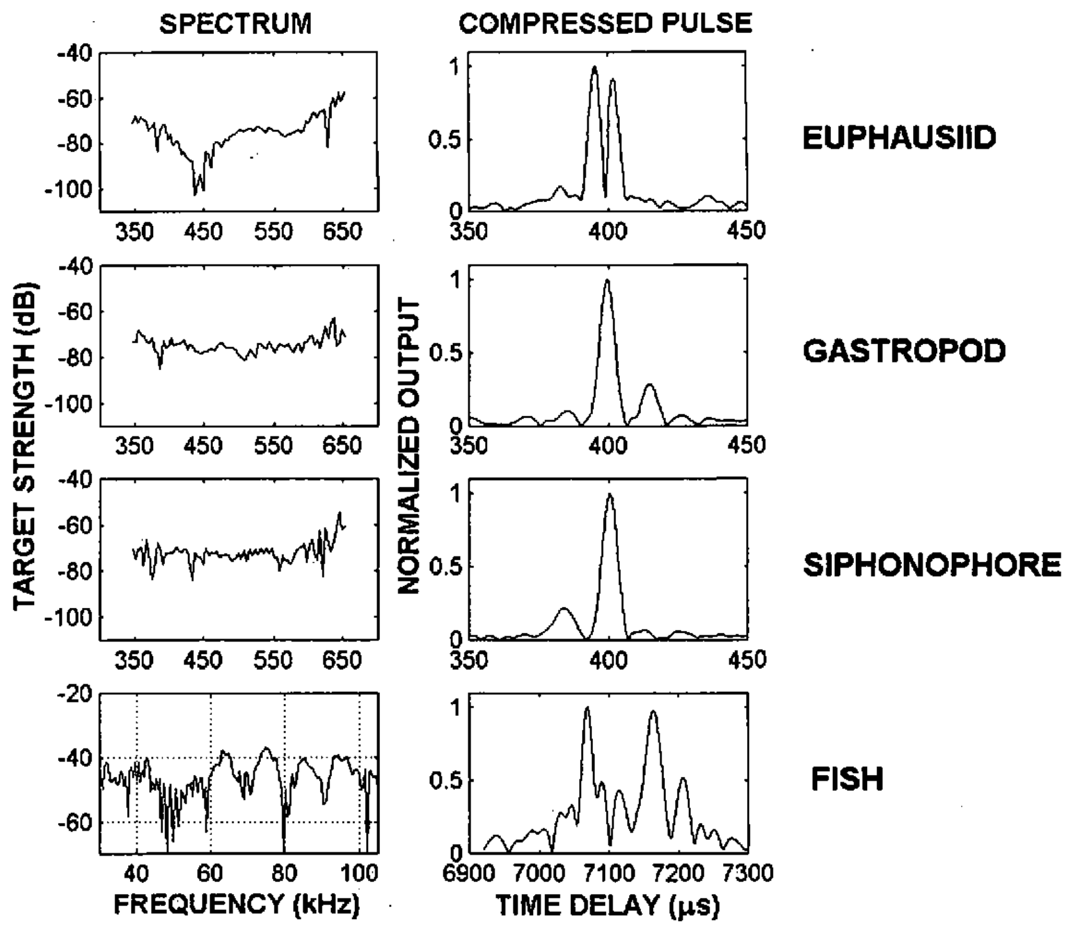

Figure 3. Spectra and pulse-compressed outputs of broadband echoes from various zooplankton [1] and fish [6]. The main lobes of the compressed pulse output correspond to scattering by features of the body such as in the case of the (alewife) fish where echoes from the skull and swimbladder are observed. For known size and anatomy, the separation between these two echoes indicate orientation of the fish.

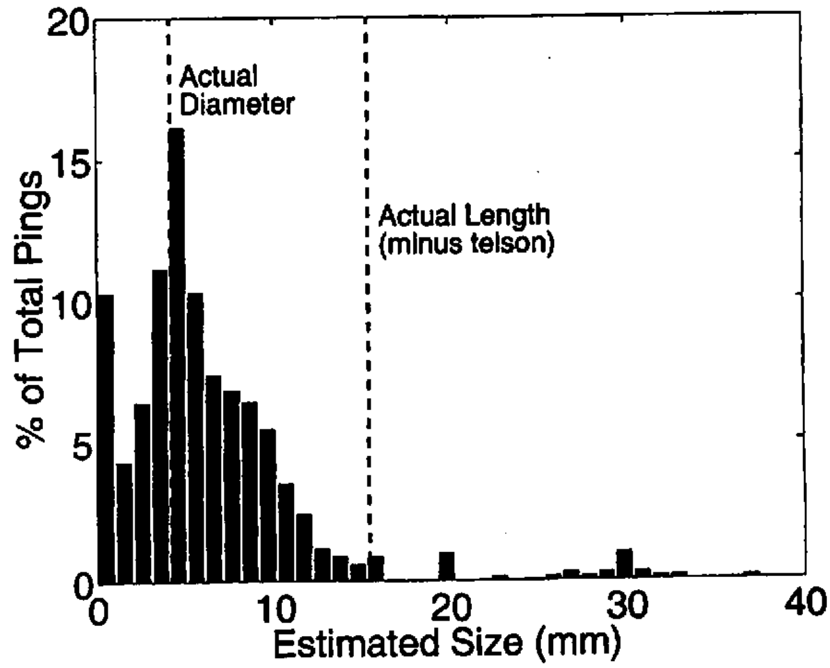

Figure 4. Temporal classification of size of shrimp using broadband echo data. Estimates derived from separation between peaks of compressed pulse output (From [5]).