PAPER

Acoustic Signatures of Three Marine Arthropods, *Squilla mantis* (Linnaeus, 1758), *Homarus americanus* (H. Milne Edwards, 1837), and *Nephrops norvegicus* (Linnaeus, 1758) (Arthropoda, Malacostraca)

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ABSTRACT

The acoustic signatures of three marine crustaceans, *Squilla mantis* (Linnaeus, 1758), *Homarus americanus* (H. Milne Edwards, 1837), and *Nephrops norvegicus* (Linnaeus 1758) (Arthropoda, Malacostraca), were experimentally determined in measurements using the calibration tank at the NATO Undersea Research Center, La Spezia, Italy. The specimens were insonified at 45° rotational intervals with a sound source emitting pings from 30 to 120 kHz. For all three species, the value of the nondimensional parameter *ka* (where *k* is the acoustic wave number and *a* is the characteristic dimension of the object) was >5. The absorption spectra, defined as the frequencies at which the intensity of the reflected sound was less than 5% of the incident intensity, were determined. These spectra changed with the changing aspects and were unique for each animal in this study. Two of the species were in the same infraorder, Astacidea. Our results contribute to the development of an acoustic identification system for surveys of marine animals.

Introduction

The detection and identification of marine animals by means of active SONAR methods offers several important possibilities for providing population data of improved quality as compared with more traditional sampling methods. Acoustic sampling methods allow the sampling of a much larger proportion of the water column without the disadvantages of avoidance and clogging of nets and bottom trawls. The results of acoustic sampling are achieved without the destruction of habitat or removal of individuals from the environment. Ideally, the researcher would like to know which organisms are living in a given region of the sea, how many are present, and how they are distributed relative to each other and to various benthic habitats. As a first step in the development of such sampling techniques, controlled experiments in the calibration tank at the NATO Undersea Research Center (NURC) may yield important useful information on the acoustic signatures of three species, which have been selected for this study.

Squilla mantis (Linnaeus 1758) is found throughout the Mediterranean Sea (Ungaro et al., 2005; Ambella et al., 2006; Atkinson et al., 1997, Maynou et al., 2004). Because of its local availability and ability to tolerate lowered salinities, this species was selected for use in these experimental studies. In addition, the American lobster *Homarus americanus* (H. Milne Edwards, 1837) and *Nephrops norvegicus* (Linnaeus 1758) were also selected because of their availability.

There have been several studies of the sounds produced by crustaceans such as those in this study. Stomatopods (Patek and Caldwell, 2006) and nephropid lobsters (Mendelson, 1969 and Henninger and Watson, 2006) are known to produce sounds by rapid muscular contractions causing the carapace to vibrate resulting in low frequency sounds <300 Hz. These

sounds are believed to be defensive in nature (Staaterman et al., 2010; Bouwma and Herrnkind, 2009; Patek and Caldwell, 2006). In this study, active SONAR is being used to identify the animals.

The density, compressibility, and speed of sound in these animals are not know with certainty, but Greenlaw and Johnson (1982) and Foote (1990) provide measurements for several different marine arthropods showing that values for the ratio of the density of the organism to the density of sea water vary between 1.010 and 1.088, that values for the ratio of celerity in the organism to celerity in seawater vary between 0.997 and 1.075, and that values for the ratio of the compressibility in the organism(s) to the compressibility of seawater vary between 0.850 and 1.075. Maaβ and Kuhnapfel (2009, personal communication) give sound speed values for various organs in the human body ranging from 1400 to 1600 m/s. These values correspond to 0.93 to 1.07 for a ratio of sound speed in soft tissues to sound speed in seawater. It seems reasonable then to assume a value of 1.04 to 1.12 for the ratio of sound speed in the animal to that of fresh water in the tank.

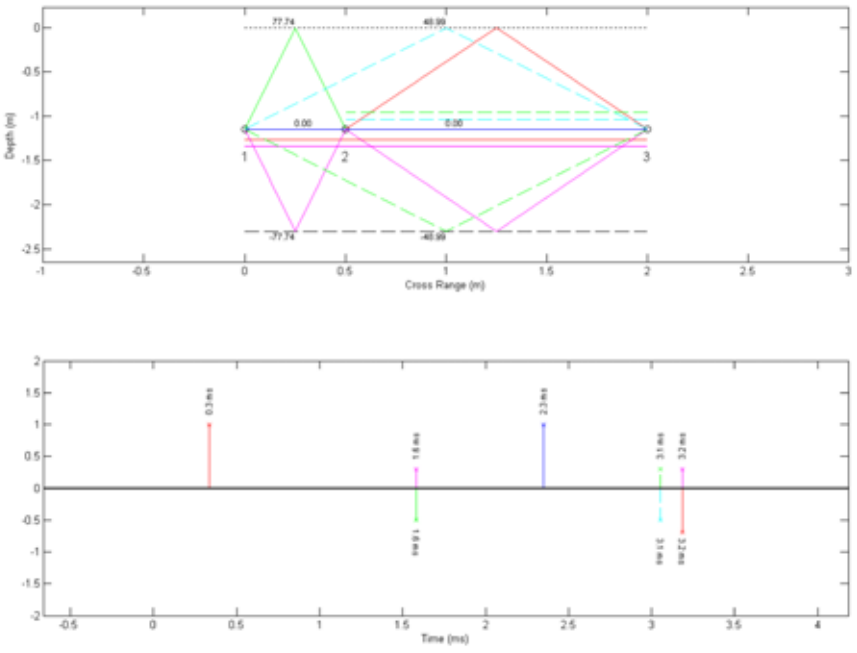
A considerable amount of research into the acoustic signature(s) of marine organisms has been accumulated, demonstrating the potential to identify marine animals by their acoustic signature. This work has included experimental studies in tanks, field observations, computer modeling, and theoretical work (Greenlaw and Johnson, 1982; Foote, 1990; Stanton et al., 1998a,b; Stanton and Chu, 2000; Roberts and Jaffe, 2008; Fornshell, 2008; Jones et al., 2009). The work done so far has clearly established the efficacy and the potential of using acoustic detection methods to sample the plankton. The ability to differentiate between taxa has been achieved (Wiebe et al., 1996; Stanton et al., 1998a,b; Lavery et al., 2007; Roberts and Jaffe, 2008). Identification to taxonomic categories below the phylum or the class level requires a significant amount of data processing and sampling at multiple frequencies (see Stanton et al. in Medwin, 2005).

In our current study, we have used the absorption between 30 and 120 kHz, notably a significantly narrow range of frequencies, compared with earlier work where two or three orders of magnitude frequency ranges were employed and generally speaking implying reduced hardware, signal processing, and data storage demands than higher frequency methods. The species in our study are much more closely related to each other than those in earlier works where taxa were differentiated. *S. mantis*, *N. norvegicus*, *H. americanus* are all members of the class Malacostraca. The last two are in the same order, Decapoda, and family, Nephropidae (Ruppert et al., 1996). The morphology of the three species is similar in that they display the basic crustacean body plan but sufficiently different that it may be expected to produce significantly different acoustic signatures.

Experimental studies on the acoustic signature of various manmade targets, some with internal inconsistencies in their physical and acoustic properties, have displayed acoustic signatures, which could be related to nonuniformities in internal structure of the SONAR target. In earlier research projects, Whispering-gallery Waves or Rayleigh Waves with wave spectra characteristics of physical nonuniformities in the targets were used to identify internal flaws in the structure of the SONAR targets. This resulted from the condition

FIGURE 1

The experimental set up in the calibration tank at the NURC. The arrival times at the receiving transducer for the initial signal, target, surface, and bottom reverberation are shown. Data collection was always terminated before sidewall reverberations arrived.



that Rayleigh Waves display dispersion in the presence of density/sound velocity variations in the medium. Such waves are relatively easy to detect in the reverberation from an object in water (Tesei et al., 2007, 2008). The back scattering may also include Lamb waves, a special form of Rayleigh Waves resulting from the displacement of a boundary between layers of significantly differing densities and sound velocities (Oraevsky, 2002). These displacements propagate both in the plane of the boundary layer and perpendicular to it. These waves are produced in experimental studies and in field studies in pelagic and benthic environments (Zampolli et al., 2008). The acoustic backscattering from the periwinkle, *Littorina littorea*, has been shown to be characterized by Lamb waves (Warren et al., 2002). In the present work, we take advantage of this phenomenon to observe the backscattering spectrum of living organisms. A clear view of the knowledge of the spectrum of the backscatter from marine crustaceans can best be obtained in carefully controlled tank experiments. With such knowledge, it may eventually be possible to identify objects on or imbedded in bottom sediments.

Experimental Methods

The experimental setup and procedures follow closely those described in experiments on solid spheres (Tesei et al., 2008). The acoustic signature of each of the three species was measured in the calibration tank at the NATO Undersea Research Center, which is 4.5 × 3 × 2.3 m, has steel walls and bottom, and is filled with fresh water. The animals were suspended with a thin nylon wire with their dorsal side up and long axis of the body in the horizontal. The source Reson TC2138 was located at mid-water at one end of the tank. Although its sensitivity is roughly flat between 40 and 100 kHz, the high signal-to-noise ratio made it possible to obtain useful data from about 15 to 100 kHz. The receiver was an omni-directional hydrophone with a roughly flat response between 1 and 300 kHz. As shown in Figure 1, it was located on the transmission axis between transmitter and target

FIGURE 2

(A) Normalized acoustic intensity as a function of wavelength from 20 to 120 kHz for *Squilla mantis*. (B) Normalized intensity as a function of wavelength from 20 to 120 kHz for *Homarus americanus*. (C) Normalized intensity as a function of wavelength from 20 to 120 kHz for *Nephrops norvegicus*.

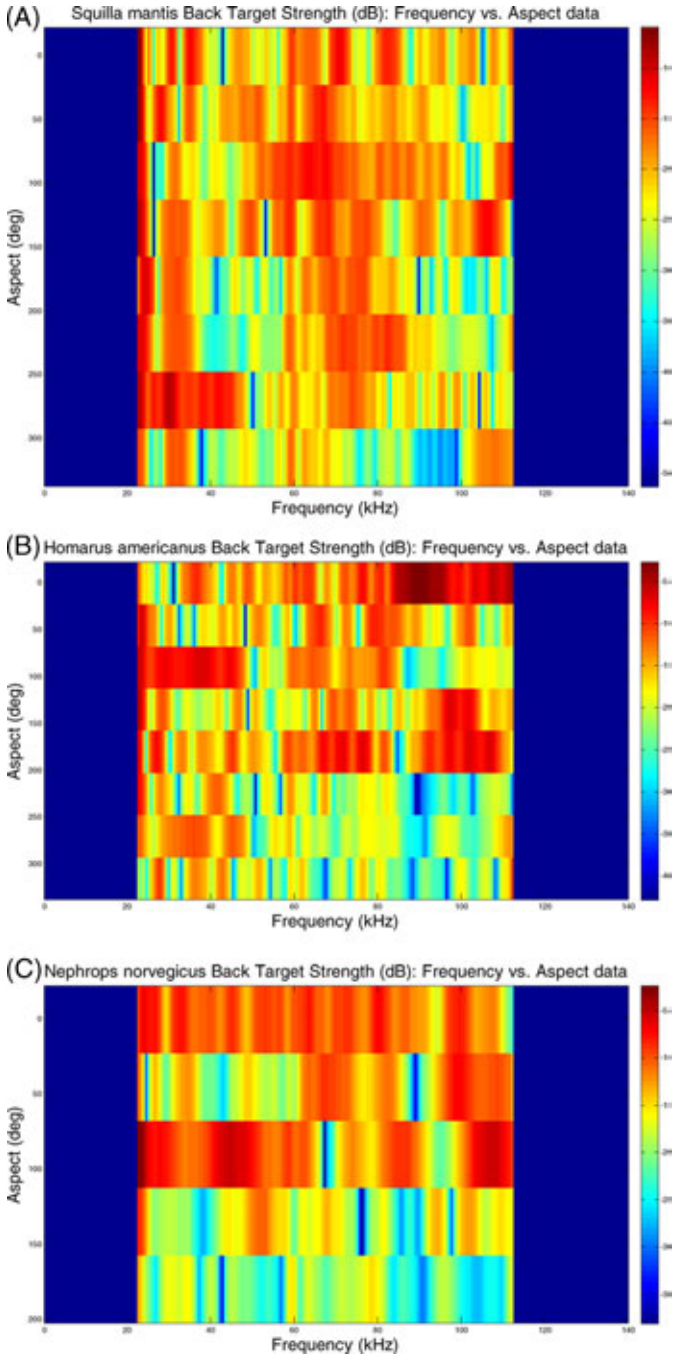


FIGURE 3

(A) Absorption spectra for *Squilla mantis* from 20 to 120 kHz. The frequencies indicated are those for which the reflected intensity was less than 5% of the incident intensity.

***Squilla mantis* acoustic signature**								
Rotation angles 000-315 (degrees) and frequency (kHz)								
000 (m)	**045 (m)**	**090 (m)**	**135 (m)**	**180 (m)**	**225 (m)**	**270 (m)**	**315 (m)**	**Frequency (kHz)**
								20
								22
X					X		X	24
		X	X	X			X	26
		X					X	28
								30
X	X							32
					X			34
					X		X	36
	X	X		X	X		X	38
		X		X	X		X	40
X				X	X		X	42
		X	X	X	X		X	44
		X			X			46
X						X		48
X				X		X	X	50
X					X	X	X	52
X	X			X	X	X	X	54
X				X	X	X		56
X				X				58
								60
			X					62
								64
								66
								68
							X	70
							X	72
							X	74
X							X	76
							X	78
							X	80
						X	X	82

continued

Continued

***Squilla mantis* acoustic signature**								
Rotation angles 000-315 (degrees) and frequency (kHz)								
000 (m)	**045 (m)**	**090 (m)**	**135 (m)**	**180 (m)**	**225 (m)**	**270 (m)**	**315 (m)**	**Frequency (kHz)**
							X	84
X							X	86
				X			X	88
				X		X	X	90
				X			X	92
			X	X		X	X	94
X				X	X	X	X	96
					X		X	98
		X		X	X	X	X	100
X	X	X		X				102
		X		X	X	X		104
				X	X			106
					X	X		108
	X			X				110

(B) Absorption spectra for *Homarus americanus* from 20 to 120 kHz. The frequencies indicated are those for which the reflected intensity was less than 5% of the incident intensity.

***Homarus americanus* acoustic signature**								
Rotation angles 000-315 (degrees) and frequency (kHz)								
000 (m)	**045 (m)**	**090 (m)**	**135 (m)**	**180 (m)**	**225 (m)**	**270 (m)**	**315 (m)**	**Frequency (kHz)**
								20
								22
	X						X	24
X	X							26
								28
X				X			X	30
					X		X	32
								34
	X							36
								38
								40
X								42
							X	44

continued

Continued

***Homarus americanus* acoustic signature**								
Rotation angles 000-315 (degrees) and frequency (kHz)								
000 (m)	**045 (m)**	**090 (m)**	**135 (m)**	**180 (m)**	**225 (m)**	**270 (m)**	**315 (m)**	**Frequency (kHz)**
					X			46
	X		X					48
		X			X			50
								52
			X	X			X	54
					X			56
							X	58
	X							60
								62
					X			64
			X				X	66
					X			68
						X		70
							X	72
	X							74
								76
								78
								80
			X					82
				X				84
		X			X	X		86
					X	X	X	88
					X	X		90
					X	X		92
		X			X	X		94
							X	96
								98
								100
					X	X		102
	X				X			104
								106
							X	108
								110

continued

(C) Absorption spectra for *Nephrops norvegicus* from 20 to 120 kHz. The frequencies indicated are those for which the reflected intensity was less than 5% of the incident intensity. The letter (m) refers to experimentally measured values and the letter (i) refers to inferred values.

***Nephrops norvegicus* acoustic signature**								
Rotation angles 000-315 (degrees) and frequency (kHz)								
000 (m)	**045 (m)**	**090 (m)**	**135 (m)**	**180 (m)**	**225 (i)**	**270 (i)**	**315 (i)**	**Frequency (kHz)**
								20
								22
	X						X	24
								26
								28
								30
								32
								34
				X				36
			X		X			38
								40
	X						X	42
								44
								46
				X				48
								50
								52
								54
				X				56
								58
								60
								62
								64
		X				X		66
								68
								70
								72
								74
			X		X			76
								78
								80
								82
			X		X			84

continued

Continued

Nephrops norvegicus acoustic signature								
Rotation angles 000-315 (degrees) and frequency (kHz)								
000 (m)	045 (m)	090 (m)	135 (m)	180 (m)	225 (i)	270 (i)	315 (i)	Frequency (kHz)
								86
	X		X		X		X	88
								90
								92
								94
			X	X	X			96
								98
								100
				X				102
								104
								106
				X				108
								110

in such a way as to minimize the surface and the bottom interference. This constraint made it necessary to locate the object at about 1.1 m from the transducer and at about 0.6 m from the hydrophone. This is sufficient to allow far field measurements of the smallest animals at 30 kHz and values of $ka > 5$. The directionality of the source, having 30° of beam width null to null at 50 kHz and side lobes –20 dB down, allowed the complete illumination of a target without strong interferences with the tank boundaries and the water surface. The residual reverberation was mitigated by subtracting a coherent average of 20 pings of scattering from the tank boundaries. Data were coherently averaged over 20 pings and equalized in the spectral domain by using the direct measurement of the transmitted pulse on the same hydrophone. The target strength data were Hamming windowed before applying an inverse Fourier transform to get a smooth time response. The transmitting and receiving transducers were calibrated to insure their proper functioning before beginning the data collection runs with live/fresh animals.

The three crustaceans species were suspended with their anterior/posterior axis in the horizontal plane. These animals were alive when placed in the tank or very fresh with no signs of decay or decomposition. The three crustacean species were insonified at 30 to 120 kHz at eight different aspects: 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. The separate source, receiver, and targets (specimens) were positioned so that there was a minimum of effects from surface, bottom, and tank sidewall reverberations. The calibration tank is 2.5 m deep, 3.5 m long, and 4.5 m wide. It is filled with fresh water. The tank geometry is shown diagrammatically in Figure 1. All acoustic observations were made at ka values greater than 5, where k is the acoustic wave number, $2\pi/\lambda$, with λ = wave length, and a is the object characteristic dimension (the length or width of the animal depending on whether it is viewed end-on or from the side). This insured that geometrical backscattering was occurring, resulting in minimizing the effects of frequency on the target strength.

The data were analyzed by performing a finite fast Fourier analysis to determine the spectra of the backscattered signal. Only the acoustic signal during a narrow time gate corresponding to the arrival time of the backscattered signal form the target animals was analyzed. The spectra were examined to determine at which frequencies the signal strength was very weak, <5% of the incident intensity. These regions were used to determine absorption spectra for each species. The bandwidth of this analysis was from 20 to 120 kHz, and

correspondingly all plots given contain valid data only over this interval. (Note that any data plotted outside of this interval is present only as a by-product of convenient data/signal processing procedures and does not affect the accuracy of the 20- to 120-kHz band of interest.)

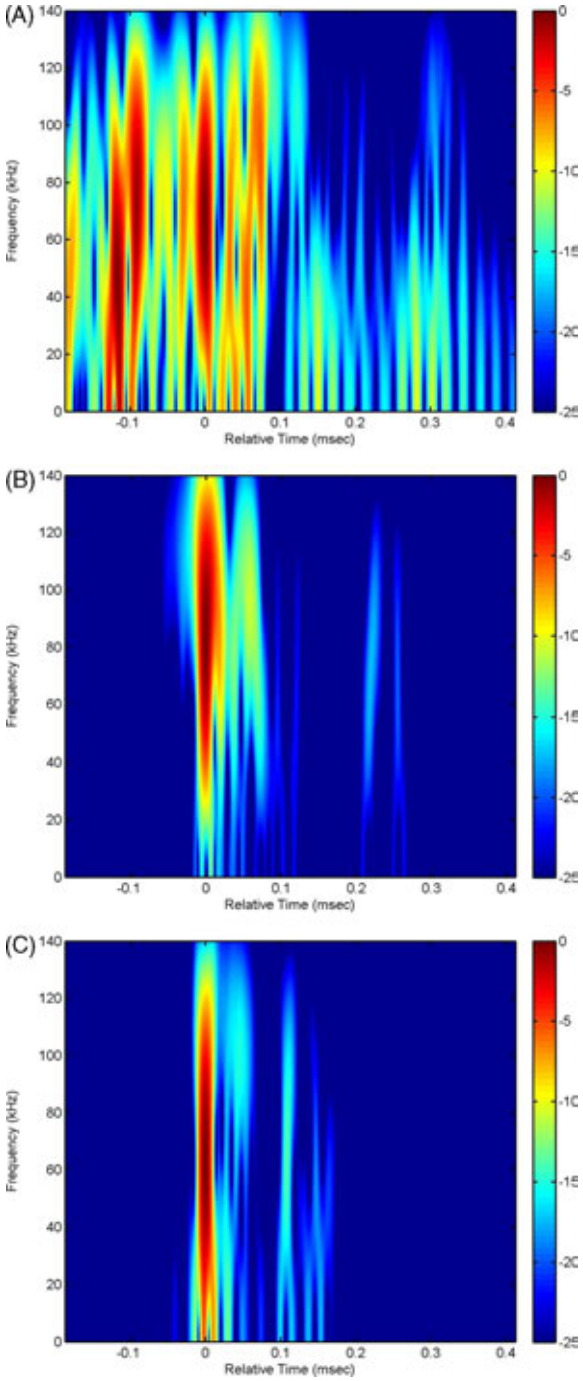
Each specimen was insonified in the frequency range of 30 to 120 kHz at different aspects (0°, 45°, 90°, 135°, and 180° for all three specimens and 225°, 270°, and 315° for *H. americanus* and *S. mantis*). Each species studied showed a unique absorption spectrum. The plotting routine used in the data analysis displayed the acoustic signal strength in 2-kHz bands.

Results

S. mantis, mantis shrimp, was placed in the tank with its longitudinal axis horizontal with the head toward the source and rotated clockwise—as in all three crustaceans. *S. mantis* has more absorption bands in the 20- to 60-kHz range than it does in the 60- to 120-kHz range (Figures 2A and 3A). It also showed more wide-absorption bands when viewed from the right-hand side, 225° to 315°, than from the left-hand side, 45° to 135°. There is an anterior posterior asymmetry in the morphology of the mantis shrimp. The specimen used in this experiment was in the process of regenerating its right-hand raptorial appendage. The regenerating appendage present was much smaller than the normal-sized raptorial appendage on the left-hand side of this specimen. The absorption bands were wider on the right-hand side than on the left-hand side. This may have accounted for the observed differences. A similar asymmetry naturally exists in *H. americanus* (Williams, 1984).

FIGURE 4

(A) Time–frequency spectrogram for *Squilla mantis* at an aspect of 0°. The signal is normalized to the maximum backscatter as 0 dB. (B) Time–frequency spectrogram for *Homarus americanus* at an aspect of 0°. The signal is normalized to the maximum backscatter as 0 dB. (C) Time–frequency spectrogram for *Nephrops norvegicus* at an aspect of 0°. The signal is normalized to the maximum backscatter as 0 dB.



The frequency versus time representation (spectrogram) of *S. mantis* data for the 0° aspect shows two very strong pulses arriving about 0.1 ms before the main reverberation response. The main response persists for 0.1 ms and is followed by a weaker response, about 30% of the initial reverberation

strength for another 0.3 ms (Figures 4A and 5A). The spectrogram for *S. mantis* for the 180° aspect displays three closely spaced reverberations followed by weaker reverberations lasting for 0.3 ms (Figures 6A and 7A).

H. americanus, the American lobster, displays fewer strong absorption bands on the left-hand side than on the right-hand side. As is normal, the left-hand claw of this specimen was modified as a crushing claw, which is much stronger and larger than the right-hand tearing claw. Except for the right posterior quarter and right-hand side, all of the absorption bands are relatively narrow. In general, the acoustic signature of *H. americanus* was much stronger than that of the preceding specimens (Figures 2B and 3B).

The spectrogram for the 0° aspect shows a strong narrow band followed by a weaker band about 30% of the maximum, reverberation arriving in the following 0.05 ms (Figures 4B and 5B). Between 0.2 and 0.3 ms after the initial signal arrives, a much weaker signal, 10% to 15% of the initial target strength, arrives. The latter may either come from internal reflections or the uropods and telson. The frequency versus time spectrogram for the 180° aspect showed a very strong initial reverberation quickly, followed by reverberations about 30% of the initial intensity during the first 0.1 ms (Figures 6B and 7B). There are relatively weak, <20% of the maximum strength, reverberations, which arrive 0.1 ms before the main signal. These may come from internal reflections or from the obliquely sloping uropods and telson, which are relatively large in this species. The left-hand side, 90° aspect, and the right-hand side, 270° aspect, were qualitatively similar. The differences were probably due to the asymmetry in the claws.

FIGURE 5

(A) Frequency response in graphical form. These are the data displayed in Figure 4A for the 0° aspect. (B) Frequency response in graphical form. These are the data displayed in Figure 4B for the 0° aspect. (C) Frequency response in graphical form. These are the data displayed in Figure 4C for the 0° aspect.

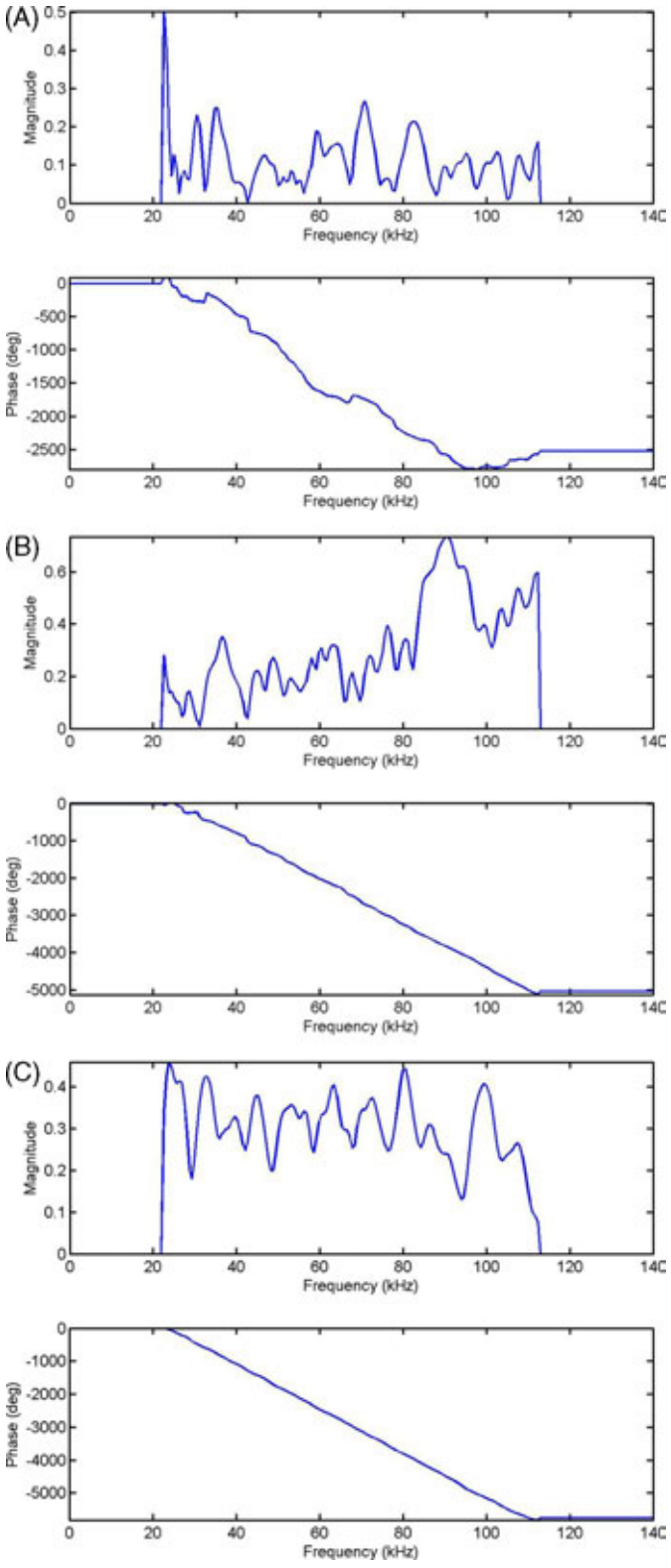
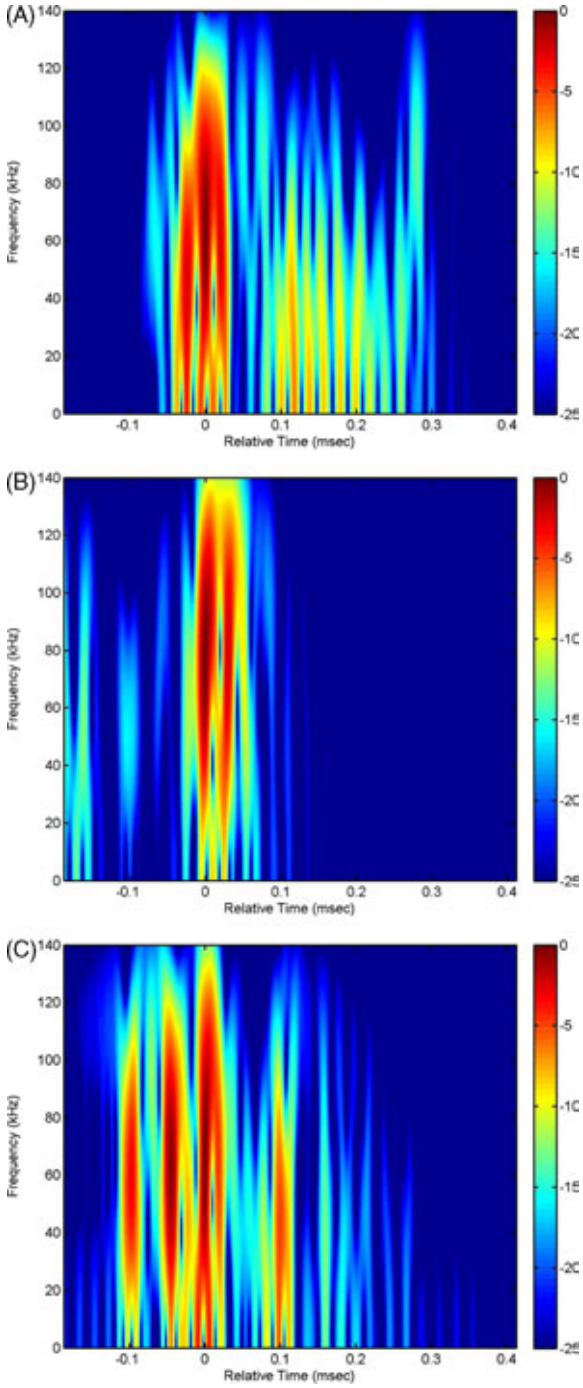


FIGURE 6

(A) Time–frequency spectrogram for *Squilla mantis* at an aspect of 180°. The signal is normalized to the maximum backscatter as 0 dB. (B) Time–frequency spectrogram for *Homarus americanus* at an aspect of 180°. The signal is normalized to the maximum backscatter as 0 dB. (C) Time–frequency spectrogram for *Nephrops norvegicus* at an aspect of 180°. The signal is normalized to the maximum backscatter as 0 dB.



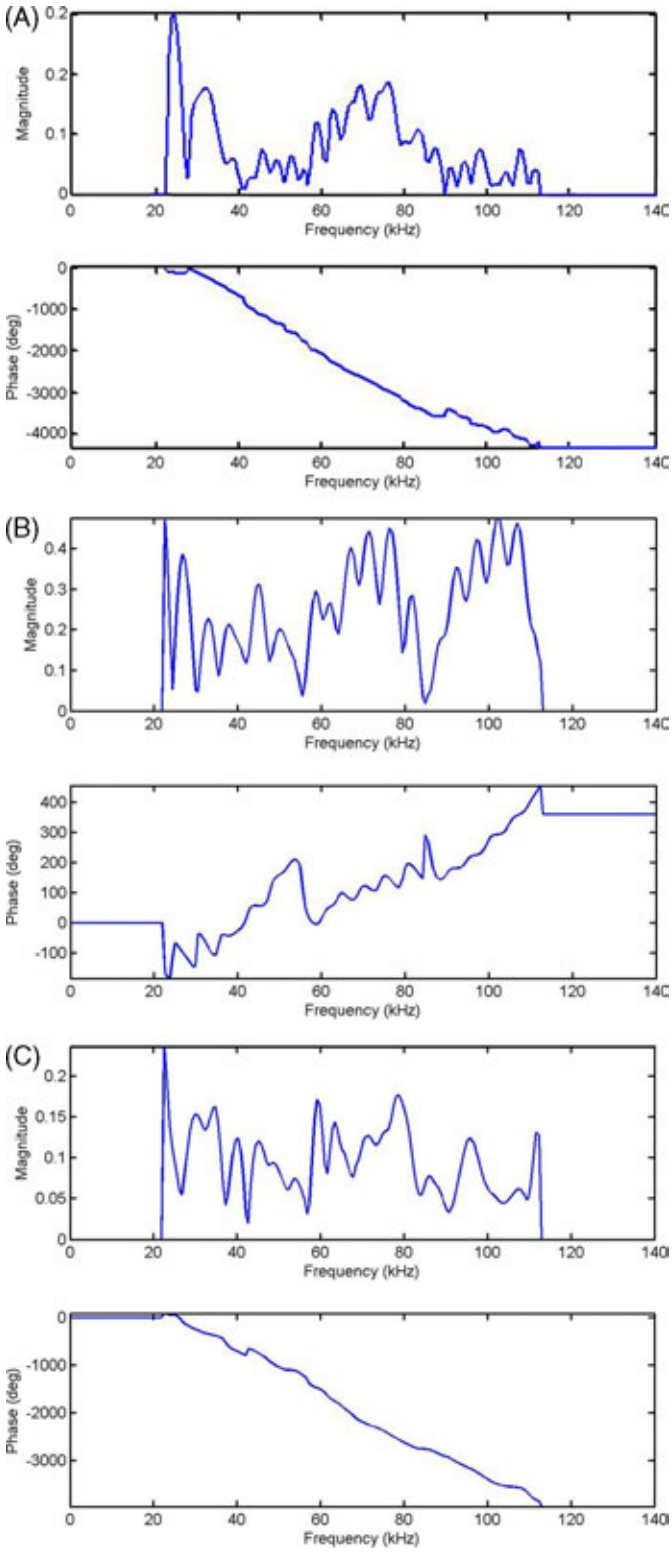
N. norvegicus, the Norway lobster, had the highest reflectivity of the four species in this study. This animal is bilaterally symmetric, lacking the crushing/tearing claw pattern of the American lobster. In anterior view, it reflected more than 5% of the incident acoustic energy throughout the entire spectrum of this study. There were no absorption bands in the frontal, 0° aspect. When viewed from the side, 90°, there was only one absorption band, three in the 45° aspect, five in the 135° aspect, and six in the posterior, 180° aspect. There was a significant anterior posterior asymmetry in *N. norvegicus* (Figures 2C & 3C).

The spectrogram for the 0° aspect of *N. norvegicus* showed a sharp initial peak with closely spaced weaker reverberations. A second wave of reverberations at about 30% of the initial intensity arrived 0.1 ms later (Figures 4C and 5C). The frequency versus time spectrogram for the 180° aspect of *N. norvegicus* showed a reverberation of about 50% of the peak reverberation strength, arriving 0.1 ms before the peak, a second such peak at about 0.05 ms before the peak, and a third about 0.1 ms after the arrival of the peak strength reverberation (Figures 6C and 7C). There were several reverberations at about 15% of the peak level throughout the spectrogram. These additional reverberations may have resulted from interaction of the incident sound waves with the animal's appendages and/or they were internal reflections.

The spectra change with aspect, but none were common between species. Previous papers have shown the potential to differentiate between very different species, such as periwinkles and euphausiids, which are on the order of tens of millimeters, but with fundamentally different body plans (Jones, 2009, and Stanton et al. in Medway, 2005). Alternately, Stanton and Chu (2000) showed the capacity to differentiate between crustaceans, euphausiids, and copepods, albeit the size differences were two orders of magnitude, tens of

FIGURE 7

(A) Frequency response in graphical form is shown in this figure. These are the data displayed in Figure 6A for the 180° aspect. (B) Frequency response in graphical form is shown in this figure. These are the data displayed in Figure 6B for the 180° aspect. (C) Frequency response in graphical form is shown in this figure. These are the data displayed in Figure 6C for the 180° aspect.



mm versus hundreds of microns. The species in this study were all in the order of hundreds of millimeters. All were arthropod crustaceans and two in fact were decapods. This was a positive step in developing an acoustic classification system for use in marine surveys.

Discussion

The potential for using acoustic spectra of marine animals as a taxonomic indicator was shown here to be a realistic objective. From this study, it appears that closely related species, like the decapods *N. norvegicus* and *H. americanus*, can be differentiated. This can also be done using a relatively narrow band of acoustic frequencies, 20 to 120 kHz. The method suggested by Stanton et al. in Medway (2005) requires using a bandwidth of two to three orders of magnitude. Acoustic signatures will require computer processing as is true of almost all oceanographic data. The acoustic signature of a single species will be a set of five to eight aspect specific absorption spectra with anywhere from one to tens of strong absorption regions in each aspect. Because they appear to be aspect dependent, relatively large numbers of potential spectra will be needed to identify different species.

As of this writing, it is not possible to correlate with any certainty these differences in spectra with internal anatomy or external morphology. Such factors as chemical composition of soft tissues, mineralization, or relative mineralization of the exoskeleton are also possible causative factors. A much larger database of course is required to make this method a viable option for population studies in the marine environment.

Although the specimens were insonified at 30 to 120 kHz, the reverberations recorded were from as low as

20 to 120 kHz. The maximum reverberation frequency reported was 115 kHz. This was an artifact of the data processing procedures.

Although the specimens were suspended in the calibration tanks for these experiments, it is important to note that similar initial studies were applicable to the detection of targets on and in bottom sediments (Tesei et al., 2007, 2008). The use of this data to detect similar specimens on or in bottom sediments is a realistic expectation.

Conclusions

Different marine arthropod crustaceans have distinct acoustic absorption spectra, which can potentially be used for the identification of the animal. The absorption spectra are aspect dependent. These spectra are distinctly different for relatively closely related species such as members of the order Decapoda and the Infraorder Astacidea.

Acknowledgments

The NATO Undersea Research Centre (Italy) is gratefully acknowledged for having hosted John Fornshell and Paul Fox as Visiting Scientists during the period of the experimental work undertaken under the NURC Visiting Researchers Program 2009 and for providing all related facilities, support, and finance during that period. The Smithsonian Institution (USA) and the Institute of Sound and Vibration Research (UK) are also thanked for their affiliated support during the completion of the work.

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