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Acoustic signature analysis of snapping shrimp noise in Australian waters

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ABSTRACT

The performance of the acoustic sensing systems can be significantly degraded by snapping shrimp noise in shallow coastal waters. These shrimps generate high-amplitude, broadband impulsive signals that pose challenges for signal detection and classification. In this study, we investigate the statistical time-frequency (TF) characteristics of snapping shrimp noise to inform the development of more robust signal processing techniques. The Smoothed Pseudo Wigner–Ville Distribution (SPWVD) is employed, which is a high-resolution TF representation, to analyse individual snap events with precise temporal and spectral localisation. Ridges are detected for each snap, and key TF features are extracted, including spectral centroid, bandwidth, ridge frequency, and TF entropy, to characterise snap variability. Our findings indicate that shrimp noise exhibits heavy-tailed, rapid spectral spread across broad frequency band within sub-millisecond durations and various TF structures. The ridges are found to be flat and localised, which confirms the absence of chirping behaviour. These insights highlight the need for adaptive, TF-aware signal processing strategies in sensing systems operating in biologically active environments.

1 INTRODUCTION

The snapping shrimp is one of the most prominent biological sources of underwater noise in shallow tropical and subtropical marine environments, such as in Australian waters. These small crustaceans produce impulsive, broadband acoustic signals known as snaps through a rapid claw closure that generates a high-velocity water jet and a collapsing cavitation bubble. The resulting impulse-like signals exhibit high energy over a broad frequency range, ranging from below 1kHz and goes above 200kHz (Cato, 1992; Potter, 1997).

Understanding the acoustic characteristics of snapping shrimp noise is crucial for multiple applications in underwater acoustics. In sonar systems, for instance, shrimp noise can mask signals of interest and degrade detection performance (Chitre, 2005; Legg, 2005). Therefore, a detailed characterisation of its temporal and spectral properties is essential. Due to this combination of high source levels and wideband frequency content, snapping shrimp noise is relevant to underwater acoustics in shallow water environments. Its impact on sonar systems provides the underlying motivation for the present study, which aims to better understand and characterise this biologically generated noise.

Previous studies on snapping shrimp acoustics have predominantly relied on time-domain analysis or broadband power spectral density (PSD) estimates (Legg, 2007). These approaches offer insights into temporal characteristics and statistics such as duration, peak amplitude, and overall spectral content etc. However, they cannot capture the dynamic evolution of energy over time and frequency in environments with overlapping snaps or multipath propagation. As a result, important features related to signal dispersion, spectral behaviour, or energy structures are understudied and need to be investigated.

Therefore, this study explores the use of the time-frequency (TF) domain to study and analyse the transient and non-stationary nature of snapping shrimp signals. Specifically, we employ the quadratic and bilinear TF distribution, which offers high resolution in both time and frequency domains (Cohen,1995). We aim to extract features by analysing the TF energy distribution of individual snaps that can be used to enhance detection, classification, or biological inference.

2 METHODS

The Smoothed Pseudo Wigner–Ville Distribution (SPWVD) is a TF distribution belonging to the quadratic Cohen's class of distributions. It is designed to provide a high-resolution representation of non-stationary signals by jointly analysing their time and frequency content (Gaunaurd, 2002). The SPWVD offers an effective compromise between time and frequency resolution and mitigates the cross-interference terms. This makes it suitable for broadband transient signal analysis in underwater environments. For a signal *x(t),* the SPWVD $\mathrm{X}(\mathrm{t},\mathrm{f})$ can be written mathematically as

$$\mathrm{X}(t,f)=\int_{-\infty}^{\infty} h(\tau)\int_{-\infty}^{\infty} g(u-t)\ x\left(u+\frac{\tau}{2}\right)x^{*}\left(u-\frac{\tau}{2}\right)e^{-j2\pi f\tau}\,du\,d\tau \tag{1}$$

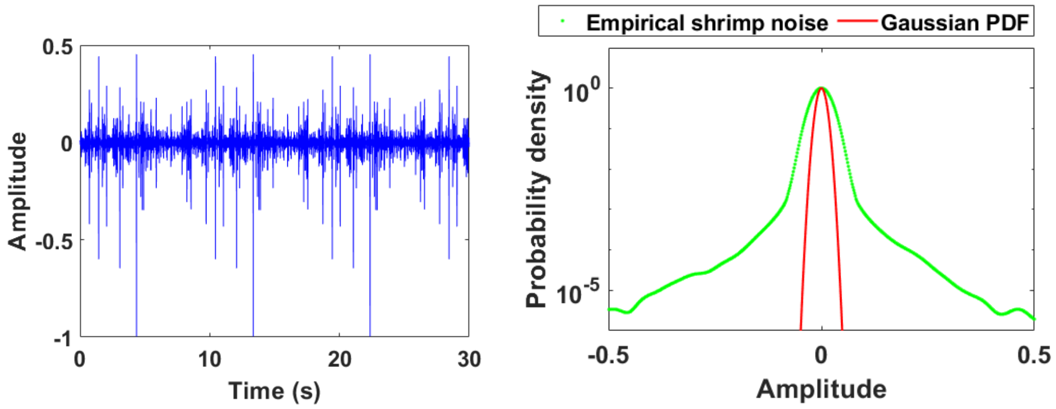
where, $h(\tau)$ and $g(t)$ are the frequency and time windows, respectively. The shorter window length in the time domain facilitates precise localisation of impulsive events, while the longer window in the frequency domain enhances spectral resolution. This asymmetric window configuration improves the robustness of feature extraction against background noise and overlapping sources. In this study, we extracted various features for each detected snap event. These features were selected based on their relevance to underwater acoustic signal characterisation and support in further modelling in sensing systems. These features are explained as follows:

- **Spectral Centroid:** Defined as the energy-weighted mean frequency at each time instant and subsequently averaged throughout each snap. This feature reflects the dominant frequency content and is indicative of the source mechanism and propagation effects.
- **Bandwidth:** Estimated as the square root of the second central moment of the SPWVD spectrum, providing a measure of spectral spread. This is useful for distinguishing between narrowband tonal sources and broadband impulsive signals.
- **Ridge Frequency:** Obtained by tracking the instantaneous frequency corresponding to the maximum SPWVD value in each time frame. The ridge captures the trajectory of dominant frequency components and is critical for TF ridge analysis and frequency-modulated signal tracking.
- **Ridge Slope:** Calculated as the first derivative of the ridge frequency over time, this feature captures the rate of frequency change and is useful in identifying chirp-like or Doppler-shifted characteristics.
- **Time-Frequency Entropy:** Computed by normalising the SPWVD to form a pseudo-probability distribution and applying Shannon entropy. This feature quantifies the complexity or sparsity of energy distribution in the TF plane, with higher values indicating diffuse, noise-like signals.
- **Temporal Centroid:** Derived from the time marginal of the SPWVD, the temporal centroid represents the mean energy arrival time and provides insight into the temporal structure and alignment of acoustic events.

3 RESULTS

3.1 Data acquisition and pre-processing

The acoustic data used in this study were acquired from the Swan River in Western Australia (WA). An HTI-96-Min hydrophone was deployed at an approximate depth of 2.5 meters at the end of the Como Jetty, where shrimp presence was acoustically prominent. The hydrophone was mounted 0.5 meter above the river bed on a steel bar and was cabled to a Sound Devices 788T recorder located on the jetty. The recorder was configured to sample at 96 kHz to resolve the high-frequency broadband content of snapping shrimp impulses. The raw data were stored in WAV format for offline analysis. Continuous recordings were divided into short-duration frames corresponding to individual snapping events to perform event-wise analysis and reduce background interference. A high-pass filter was applied with a stop frequency of 400 Hz and a pass frequency of 900 Hz to remove flow-induced low-frequency artefacts unrelated to shrimp-generated transients. Figure 1 shows the temporal characteristics of the collected dataset. Multiple transients or impulses can be seen in the 30s segment. Figure 1 (b) compares the typical Gaussian distribution and the distribution of the collected shrimp noise data. The figure shows the heavy-tailed, non-Gaussian impulsive behaviour of shrimp noise.

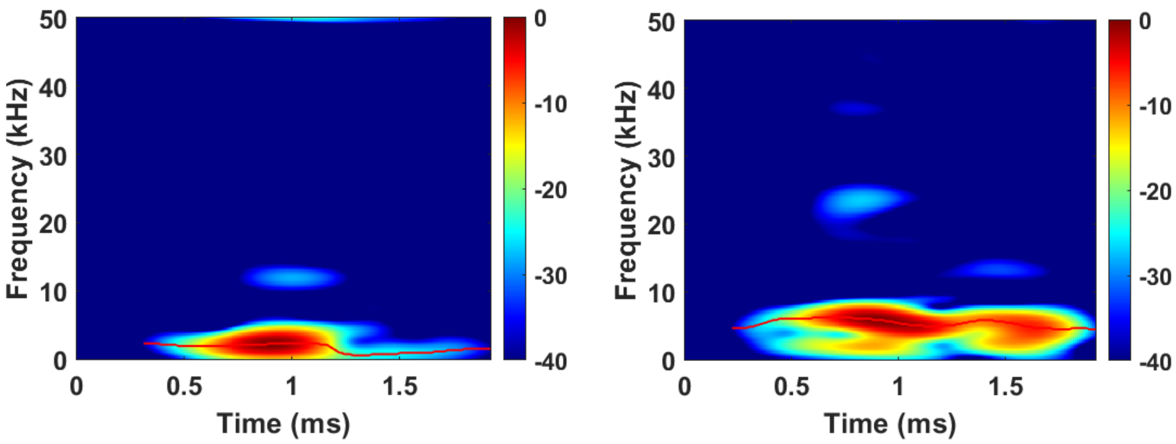


(a) (b)

Figure 1: (a) Time-domain waveform of snapping shrimp noise. (b) Probability density function (PDF) of shrimp noise overlaid with a Gaussian PDF.

3.2 Acoustic TF analysis

Snapping events were detected using an energy-based thresholding method applied to short time frames (0.5 ms) of the normalised signal. A snap was identified when the maximum absolute amplitude within a frame exceeded four times the signal's root mean square (RMS) value. Then, SPWVD representations were computed for each snap using short-time windows with Hann smoothing functions of 41 and 61 samples for time and frequency smoothing, respectively. The window lengths are identified after careful tuning to ensure effective time localisation and frequency smoothing. For each detected snap, the resulting SPWVD matrix was visualised in dB scale. To further interpret the TF structure, ridge detection was applied by extracting the frequency corresponding to the maximum energy at each time slice. This was implemented by identifying the peak across frequency bins within the SPWVD at each time frame. The ridge represents the dominant energy trajectory of the signal.



(a) (b)

Figure 2: SPWVDs of two snap events with the detected ridges.

Figure 2 (a) illustrates a snap event with more compact time-frequency localisation and structure. Whereas Figure 2 (b) shows a second snap event exhibiting strong broadband energy concentrated between 5–10 kHz with visible spectral smearing and a secondary component or another snap. Analysis of the ridges showed that most snapping shrimp signals do not exhibit chirping behaviour; instead, their ridges are flat or vertically clustered. Subsequently, the extracted ridges from each snap event are further used to extract six important features to gather insights about the nature of snaps. These features have already been discussed in the previous section. The scatter plots across individual snaps are shown in Figure 3. This figure presents the distribution of the features extracted from 5,000 individual shrimp snaps using SPWVD ridges. Each subplot illustrates the variability and structure of a specific feature across all detected events. Most snaps have dominant frequency content centered in the low-to-mid frequency band,3-10 kHz. They are broadband; however, some variability exists due to propagation and multipath overlapping. Most ridge slopes cluster around zero, which indicates stationary frequency content, i.e., no chirping. However, occasional sharp slopes hint at possible multipath or transient frequency shifts. Entropy rates are noted as high at 10-12 mostly, which indicates the diffuse energy distribution in the TF plane. This further confirms that snapping events are non-tonal.

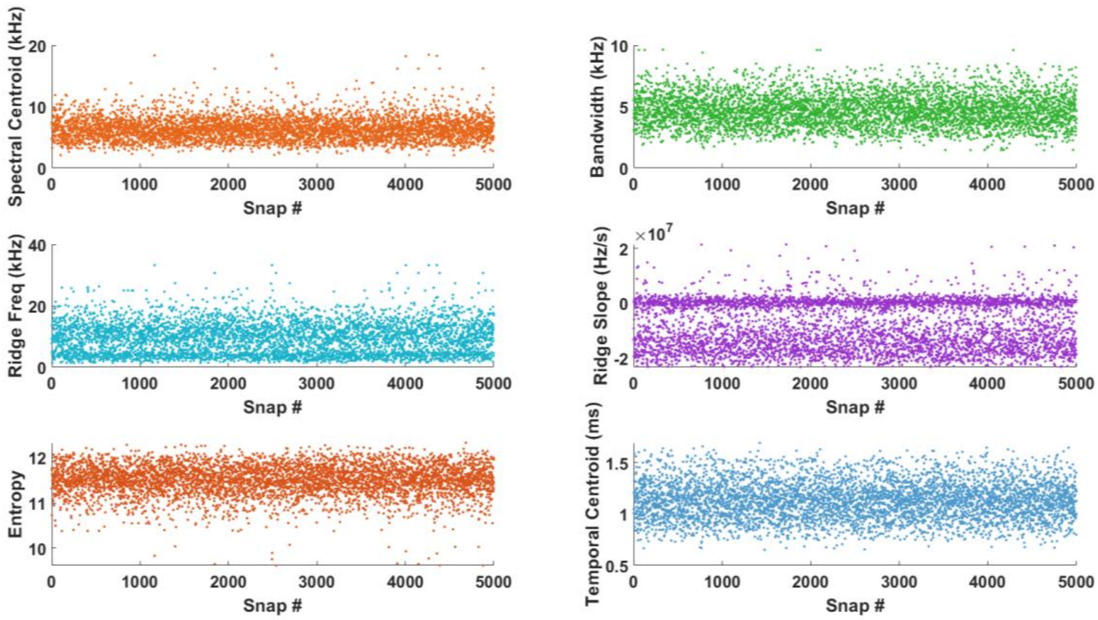


Figure 3: Scatter plots of features extracted from 5,000 individual shrimp snaps using SPWVD ridges.

4 CONCLUSION

This study presented a detailed time-frequency analysis of snapping shrimp noise to improve the understanding of snapping shrimp snapping behaviour, with its implications on acoustic signal processing and detection. Using the SPWVD representation, we extracted important time-frequency features from several individual snap events. The analysis revealed that shrimp snaps from the Swan River, WA dataset exhibit high spectral variability, broadband energy distribution concentrated around 5–15 kHz, and consistently high time-frequency entropy. Moreover, the absence of chirping behaviour observed in shrimp snaps can serve as a discriminatory feature for differentiating them from sonar chirp signals. These findings offer a foundation for building adaptive and TF based filtering techniques that can enhance the robustness of underwater sensing in biologically active and cluttered acoustic scenes.

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