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Cyclostationarity for Passive Underwater Detection of Propellor Craft: A Development of DEMON Processing

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ABSTRACT

As the blades of a propeller pass through the water they produce characteristic amplitude modulated random noise signals which can be detected using sonar. A popular empirical technique for passive acoustic detection of surface ships from submarines using these sonar signals is DEMON (Detection of Envelope Modulation on Noise) processing. As the name suggests, DEMON processing seeks to detect the frequencies of modulation, i.e. the shaft and blade pass frequencies. It works by isolating the frequency band in which the modulation is most distinct to the operator, taking the envelope of this filtered noise band and producing a waterfall spectrogram. Harmonics associated with the rotating components of the propeller will be manifest in the waterfall, allowing the vessel to be identified. DEMON processing has several drawbacks however, most importantly the requirement for operator skill in the selection of the noise band. This paper presents the preliminary findings of work underway to provide a mathematical formalisation of the empirical DEMON processing technique. This formalisation is based on the observation that DEMON processing unknowingly exploits the cyclostationary properties of the propeller signals. Cyclostationary signal processing, a technique which has recently found application in mechanical systems involving rotating machinery, offers great insight into the detection problem, and has the potential to overcome the weaknesses of DEMON processing as well as expanding its capability to include frequency as well as amplitude modulation.

INTRODUCTION

Of key interest to submariners is the ability to detect the presence of surface ships while remaining undetected themselves. To this end, passive detection techniques have been developed whereby the surface ship is detected, and in some cases classified, based on its noise emissions which are recorded by hydrophones on the submarine.

Detection is impeded when the signal from the ship is lost in the noise, which can occur when the marine environment is particularly noisy and/or when the ship is distant from the submarine. In order to maintain contact with a target vessel, the detection must rely on some form of signal processing to enhance the acoustic signature of the ship and attenuate the extraneous components in the sonar signal. This paper examines one such technique, DEMON processing, which relies on the periodicity in the ship acoustic signature created by the rotating propeller blades.

THEORETICAL OVERVIEW

The Search for Hidden Periodicity

The quest for passive identification of propeller craft from sonar signals can be restated as the search for hidden periodicity in (presumably) uncorrelated noise. The periodicity arises from the rotation of the propeller blades, and the uncorrelated and often broadband noise is a feature of the marine background acoustic environment.

Signals combining random and periodic components are commonly encountered in e.g. mechanical applications. Machines with rotating components such as shafts, gearboxes and bearings are common, and a principle feature of condition monitoring of gearboxes and bearings, structural dynamics involving rotating machinery and vehicle dynamics, is the separation of these random and periodic components. The simplest technique for achieving this separation is time synchronous averaging. This involves taking the ensemble average of sections of the signal which are equal in length to the period of the harmonic component of interest. All other components are diminished by the averaging, leaving only the periodic component (see e.g. Peeters et al, 2007). This technique demands that the period is both precisely known and constant, which may not be the case in blind mechanical applications such as passive detection. If the cycle could be readily identified, then order tracking could be employed to overcome any variation in the period of the harmonic component, but this is unlikely to be the case in such a noisy environment.

Another popular technique for the separation of random and periodic components has been self-adaptive noise cancellation (Antoni and Randall, 2004a) which in recent times has been refined in the form of the Discrete-Random Separator

(DRS) (Antoni and Randall, 2004b). The DRS exploits the difference in correlation length between the random and periodic components in the signal to design an H1 style filter which extracts the periodic components in the frequency domain. In this way it is not susceptible to changes in the cycle of the periodic component, and does not rely on the precise identification of its period. Its utility was demonstrated through industrial applications involving modal analyses of a paper machine (Antoni, et al, 2004) and a stadium cantilever stand (Hanson, 2007).

Another technique for separating periodic components from broadband noise is liftering in the cepstrum domain. In the cepstrum of such a signal, the periodic components would manifest as a train of rahmonics which can be removed by liftering. The signal can then be transformed back to the frequency or time domain and will comprise of only its random constituents. This technique has been applied to echo removal, double bounce removal from impact hammer response signals, and many machine condition monitoring applications (see e.g. Randall, 2000 and Gao and Randall, 1996). Indeed, it is already used in underwater acoustics to remove the first reflection components from sonar signals recorded in shallow water (Coates, 2001).

This paper discusses a different technique, developed empirically in the field of underwater acoustics, known as DEMON processing. This will be discussed below, but first the nature of the propeller signal will be examined in more detail.

Propellor Noise Signal

The principal source of acoustic energy in the propeller signal is provided by cavitation (Sharma et al, 1990). Cavitation is a process whereby bubbles are drawn out of the water by pressure gradients on the blade surface and edges. These bubbles are unstable, and it is their collapse that produces the noise. The spectral content of propeller cavitation noise is quite broadband, with significant energy out to at least 100kHz, as shown in Figure 1.

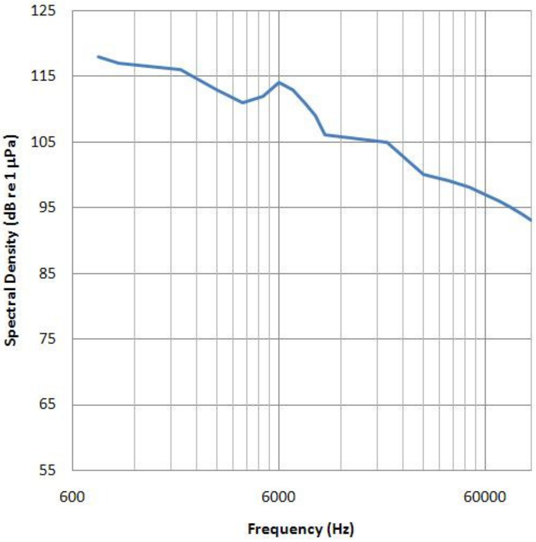
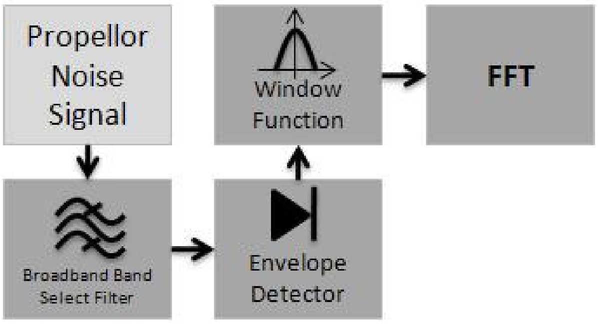


Figure 1 Typical propellor noise spectrum (reproduced from data scaled from Fig. 5 in Sharma et al, 1990)

The degree of cavitation is related to the water pressure which varies with depth. Therefore, the cavitation noise will modulate as the propeller blade rotates through varying water depth. The propeller signal is thereby comprised of amplitude modulated cavitation components, with a modulation period akin to the propeller frequency. Expressed another way, the propeller signal can be seen to be made up of a broadband carrier component modulated by the periodic blade rotation. The challenge of DEMON processing is to extract the periodic component.

DEMON Processing

DEMON processing (DEtection of Modulation On Noise) is a technique employed by submariners to detect the presence of propeller craft. It uses the FFT of the envelope of band pass filtered sonar signals to emphasise the modulation in time of the pressure signal (see e.g. Coates 2001). This technique appears to be largely empirical, with few papers in the literature. Recently an extension to the technique was made by Li and Yang (2007) who employ higher order statistics to suppress Gaussian noise, but the current investigation addresses the basic DEMON processing technique, as outlined in Figure 2.



Source: (Coates 2001)

Figure 2 Schematic of DEMON processing procedure

It can be seen here that an integral part of DEMON processing is the design of the band pass filter. Traditionally, this has been the domain of trained sonar operators who manually tune the pass band to emphasise the periodic components in the sonar signal associated with the blade pass, i.e. the modulation of the cavitation signals. Kummert (1993) proposes to replace the human operator with optimally tuned filters based on fuzzy logic, but the process employed still follows that described in Figure 2.

An example of the principles of DEMON processing is shown in Figure 3. Here is represented an amplitude modulated broadband signal and its corresponding spectrum, which is basically white in the frequency range of interest, i.e. the modulation does not manifest as identifiable harmonics. Also shown is the envelope of the band pass filtered signal, and its spectrum, in which the first harmonic of the modulation frequency is clearly evident. By DEMON processing therefore, the periodic modulation is transformed into a discrete frequency component which can be identified in the spectrum.

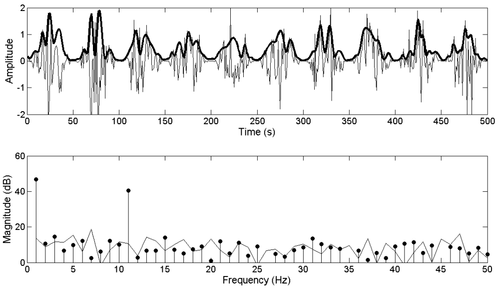


Figure 3 periodically modulated broadband signal (top), its spectrum (solid line) and the spectrum of its envelope (dots) (bottom)

Expressed in another way, DEMON processing approaches the search for hidden periodicity phrased above, by attempting to transform the second order periodicity inherent in the propeller signal to first order periodicity through the signal envelope. By so doing, long established time-frequency signal processing techniques can be applied. Significant advantages exist however, in utilising the second order periodicity explicitly. Indeed, an entire toolbox is made available by recognising that the amplitude modulated propeller signal belongs to a special class of signals known as cyclostationary.

Cyclostationarity

The term "cyclostationary" refers to a special class of non-stationary signals which are random in nature, but exhibit periodicity in their statistics. A first order cyclostationary signal (CS1) will exhibit periodicity in its first order statistics, i.e. its ensemble mean will be periodic; at the second order, its autocovariance. Consider a burst random signal as represented in Figure 4.

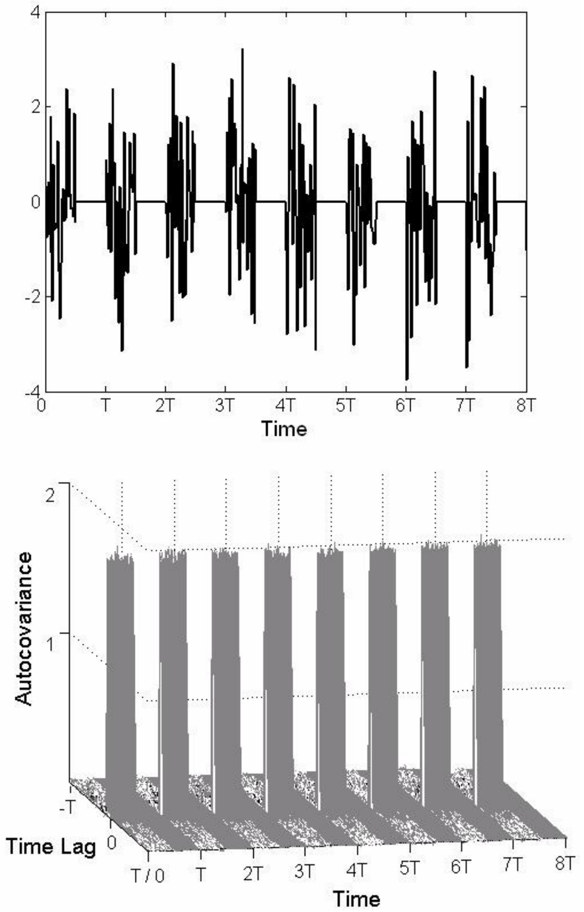


Figure 4 Periodicity in the autocovariance of a second order cyclostationary signal; a section of a burst random signal (top) and its estimated autocovariance (bottom)

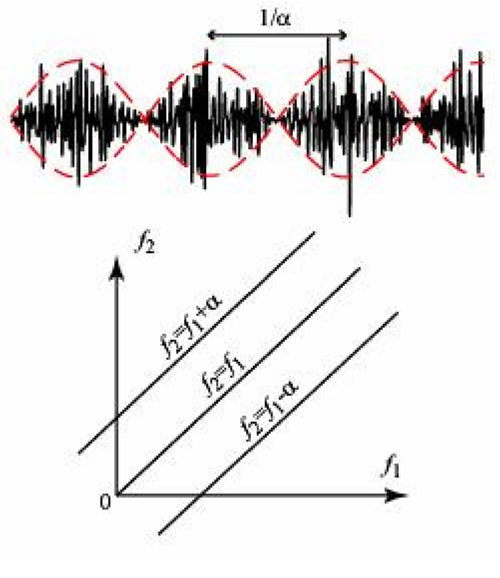
The first order statistics of the signal, i.e. the ensemble average over one on / off cycle, is zero and so not periodic. However the autocovariance (a second order statistic) of the signal can be seen to exhibit periodicity in time *t*. Therefore, this signal may be described as second order cyclostationary (CS2).

Of particular importance to this work is the cavitation of propeller blades as they pass through the water. Like the burst random signal above, the cavitation from each blade pass may be considered as broadband and random, but they occur in a periodic fashion related to the shaft speed and are cyclostationary at the first and higher orders.

An important property of a cyclostationary signal is the cyclic period "T", which is the period of repetition observed in the statistics and is often described by its frequency domain analogue, the cyclic frequency "α", where $\alpha = \frac{1}{T}$.

Correlation in the Frequency Domain

Another way to examine cyclostationarity is through the concept of correlation in the frequency domain, as explained by Antoni (2008). Antoni examines a stationary random carrier signal modulated by a harmonic function of period 1/α, as shown in Figure 5. Given that the signal is stationary random, we would expect that non-zero correlation exists only for the case where $f_1 = f_2$, i.e. where the corresponding frequency components in the two signals are aligned in the correlation. Indeed, as Figure 5 reveals, the two signals exhibit correlation along the line $f_1 = f_2$. In addition however, it can be seen that correlation exists for either signal shifted by α (nb: actually any integer multiple of α). Antoni expresses this relationship in reverse, explaining that it is the spectral components spaced apart by α which are interfering in such a way to produce the periodic modulation in the time domain.



Source: (Antoni, 2008)

Figure 5 Correlation in the frequency domain of a random carrier signal with harmonic modulation

This correlation can be exploited to identify the propeller components in a noisy sonar signal. Rather than focusing on the temporal evolution of the modulation (cyclic) frequency, i.e. time-frequency spectrum, further insight can be gained by examining the frequency-cyclic frequency spectrum. This will be examined in the next section.

This work makes use of the cyclic modulation spectrum, which is calculated from the DEMONgram (time-frequency spectrum) by taking the Fourier transform of the squared signal along the time axis:

$$P(\alpha, f) = \Im_{t \to \alpha}\left\{\left|X(t, f)\right|^2\right\} \qquad (1)$$

where $\Im_{t\rightarrow\alpha}$ means the Fourier transform from time t to frequency α and *X*(*t*,*f*) is the short-time Fourier tansform of signal *x* centered around time *t*.

This produces a two dimensional spectrum in terms of frequency and cyclic-frequency (frequency shift). The frequency domain correlation manifests as a non-zero spectrum at the modulation frequency, which may contain useful spectral information in its own right. Only the magnitude is examined here however, as the intent is limited to identification, rather than diagnostics.

The cyclostationary technique employed in this investigation can be summarised in the simple block diagram shown in 6.

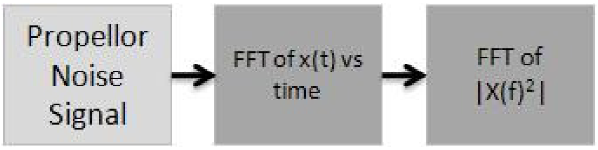


Figure 6 Schematic of cyclostationary propeller detection process

It should be noted that the same uncertainty principle applies to the cyclic modulation spectrum as to the instantaneous power spectrum, i.e. the reciprocal of the time resolution Δt is the largest cyclic frequency $\alpha_{\max}$ that can be identified:

$$\alpha_{\max} \le 4\pi\Delta\,\mathrm{f} \qquad (2)$$

The DEMON processing and cyclostationary techniques are compared in the next section using both simulated and measured signals.

RESULTS

Simulation

The proposed cyclostationary processing was compared with the DEMON processing technique through a simulation. A propeller signal was created as a summation of modulated random noise where each cycle was described by:

$$y(t)=\sum_{n=1}^{M} x_n(t)w_n(t) \qquad (3)$$

where $x_n(t)$ are different broadband noise signals for each blade, randomly sampled from a Gaussian distribution, $w_n(t)=\frac{1}{2}\left[1-\cos\left(2\pi\frac{2t}{T}\right)\right]$ for $\frac{n-1}{M}T<t<\frac{n+1}{M}T$ and is zero elsewhere, and where *T* is the period of the propeller shaft ($T = {}^{1}\!/_{f_{shaft}}$). This constitutes a propeller with *M* blades, rotating at f_{shaft} on which each blade induces cavitation only across the top of its cycle, i.e. where the water depth is smallest. The signal is represented in Figure 7 where the shaft speed was 8Hz, the sampling frequency was 20 kHz and there were four blades on the propellor. Note that this simulation represents the idealised noise-free case.

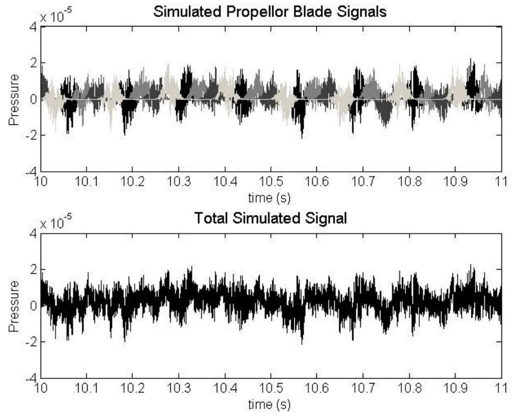


Figure 7 Simulated propeller blade signals (top) and total propeller signal (bottom)

The selection of pass band frequencies was somewhat arbitrary, there being no guidance provided in the literature. It was therefore decided to employ third octave bands, with the the 1250Hz third octave band returning the best results in this case. These results are shown in Figure 8.

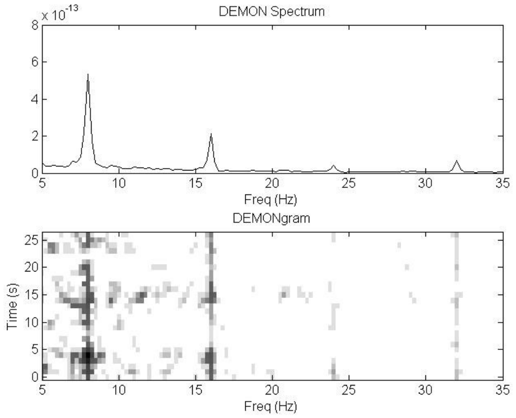


Figure 8 Results of DEMON processing on the simulated propeller signal

The cyclic modulation spectrum requires no pre-filtering however, and the results of this analysis are shown in Figure 9.

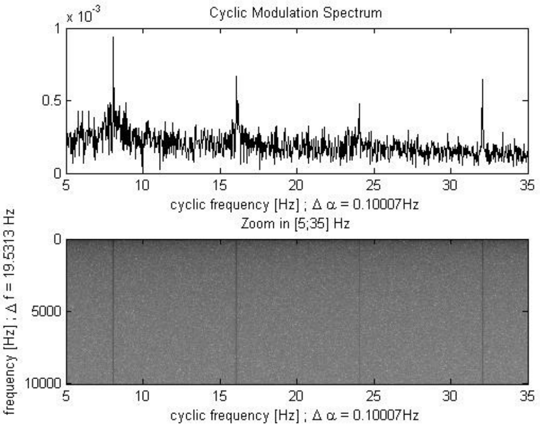


Figure 9 Cyclic modulation spectrum of the simulated propeller signal

Both techniques were successful in identifying the shaft and blade pass frequencies. As expected, the harmonics of shaft speed decrease in magnitude with increasing frequency. The exception however is the *M*th harmonic of shaft speed, where *M* is the number of blades on the propellor, i.e. the blade-pass frequency, which exhibits a characteristic increase in magnitude. This allows the number of blades on the propeller to be determined, and combined with the shaft frequency, assists in the blind identification of the vessel type.

It is evident from these two figures that the cyclic modulation spectrum affords superior (cyclic) frequency resolution compared with the DEMONgram (i.e. time/frequency analysis).

North Sea Coaster

The two techniques were also applied to a sonar signal of a North Sea Coaster, recorded by Professor Rodney Coates off the coast of the United Kingdom. Although this recording was made in shallow water, the rahmonics associated with first reflection were not evident in the cepstrum of the signal, as shown in figure 10. Such components, if present, can be removed by liftering (see e.g. Randall 2000).

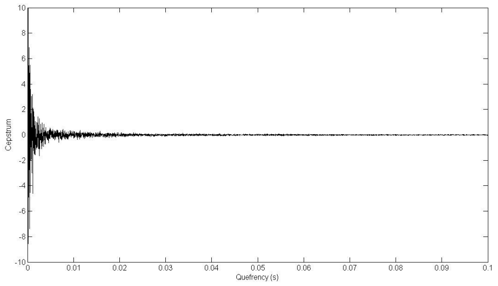


Figure 10 Cepstrum of a section of signal from the North Sea Coaster

The results of DEMON processing on this signal are shown in Figure 11.

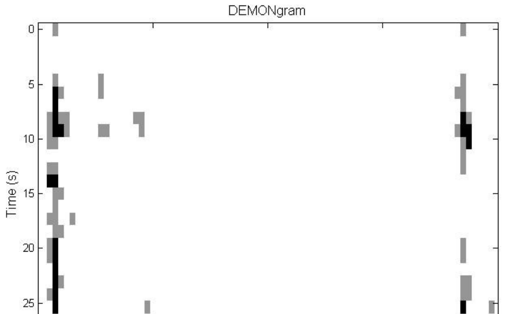


Figure 11 DEMONgram of the North Sea Coaster signal

The DEMON processing technique was not clearly able to discriminate the harmonics of shaft speed, but clearly identifies the shaft speed (~5.75Hz) and blade pass frequencies (~23Hz). It should be noted that the selection of pass bands was again arbitrary (third octaves) and it is possible that an experienced sonar operator would return superior results using this technique to those shown in Figure 11

The cyclic modulation spectrum is insensitive to such considerations however, and clearly identifies the shaft speed and its harmonics, and the blade pass frequency, as shown in Figure 12.

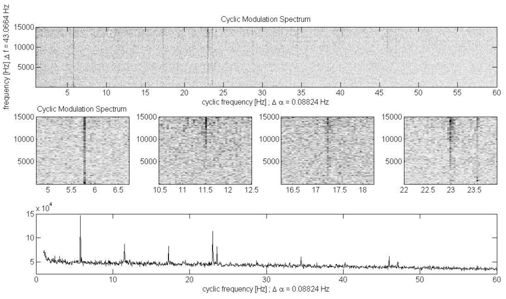


Figure 12 Cyclic modulation spectrum of the North Sea Coaster signal (top), zoom on each harmonic (middle) and mean cyclic frequency spectrum (averaging along frequency axis) (bottom).

Furthermore, the superior (cyclic) frequency resolution afforded by the cyclic modulation spectrum makes it possible to discriminate paired harmonics of shaft speed and blade pass – perhaps associated with two propeller shafts operating at slightly different speeds (in this case approximately 8rpm). Indeed, this technique allows the modulation to be detected over a wide frequency region whilst maintaining the fine cyclic frequency resolution. DEMON processing however, requires that the modulation be detected over a relatively narrow frequency range, thus requiring significant guess work in designing the filter passband.

DISCUSSION

This paper presented the preliminary findings of the development of a new technique for passive underwater acoustic detection of propeller craft. This new technique was based on cyclostationary signal processing, and exploited the spectral redundancy inherent in the propeller signal to blindly idenfity the shaft speed and number of blades of the propeller when the signal was buried in uncorrelated noise. This technique was proposed as a development of DEMON processing, which is an empirical technique that employs user defined band-pass filtering and envelope analysis to extract the propeller components from the noisy signal. The cyclostationary technique was shown to offer superior detection properties in that the harmonic components of interest were more readily identifiable than with DEMON processing, no user interaction was required making the technique more robust, and higher frequency resolution could be achieved thereby allowing the identification of multiple shafts (if present).

The technique was compared with DEMON processing using both simulated and measured signals. In both cases, the cyclostationary technique was able to identify both the shaft speed and the number of propeller blades.

FURTHER WORK

Combating the Snapping Shrimp

One particularly potent adversary of sonar operators in tropical waters is the snapping shrimp (*Alpheus, Synalpheus*, Coates 2001). These tiny shrimp have dissimilar pincers, one like a tiny plug and other like a suitably sized pocket, that the shrimp snap together to produce a loud report. The noise is not generated directly by the contact of the two pincers, as might be expected, but rather by the collapse of a cavitation bubble which the snapping action has created.

The duration of the event is sufficiently short to produce a white spectrum out to more than 100kHz. While one tiny shrimp is able to generate sufficient noise to be clearly heard from outside an aquarium, in tropical waters where they exist in the billions, their collective efforts can render sonar completely ineffective.

The DEMON processing technique cannot cope with this noise either. Any temporal modulation associated with the propeller signal would be swamped by the broadband noise offered by the shrimp. The cyclostationary properties of the signal would not be so adversely affected however. Provided that the signals generated by the shrimp were a) not cyclostationary, or b) cyclostationary but with a different cyclic frequency to the propeller signal, then the cyclic modulation spectrum at α_{shaft} would be unaffected by the shrimp noise.

If the shrimp signal was cyclostationary, i.e. if the shrimp were snapping with a regular cycle, then the detection of the propeller craft would rely on identifying the cyclic frequency components associated with the propellor as opposed to those associated with the shrimp. This could be achieved by simple observation, given that the shrimp cyclic frequency would be very much higher than that of the propeller, or by more sophisticated means, possibly associated with the characteristic increase in the magnitude of the blade pass harmonic.

Automatic Detection Algorithms

One advantage of the cyclostationary approach is that it potentially enables the calculation of statistical thresholds for the fully automatic detection of hidden periodicities. In this way, the technique could be employed in real time monitoring, with alerts presented to operators only when a threshold is exceeded.

Cyclic Spectral Density and Cyclic Coherence

The Cyclic Modulation Spectrum employed in this investigation is the most basic representation of the cyclostationary metrics which can be employed to describe the signal properties. Further enhancements could be made by introducing the cyclic spectral density and cyclic coherence. These are, respectively, the spectral density between a signal and a frequency shifted version of itself, and the coherence between two signals evaluated at a particular cyclic frequency (frequency shift). The advantages of these metrics over the basic cyclic modulation spectrum include superior frequency resolution and averaging of uncorrelated noise components. In the case of the cyclic spectral density, at each cyclic frequency a non-zero cyclic spectrum is obtained. The cyclic spectrum may contain spectral information which allows further diagnostics of the propeller craft, e.g. each craft or type of craft may present a unique cyclic spectrum which may aid the identification of particular vessels.

ACKNOWLEDGEMENTS

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