Detection of Helicopter Signals Using Cyclostationarity

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Abstract

Experimental results on the study of helicopter acoustic signals with nonstationary additive noises using cyclostationarity are presented. It is shown that helicopter signals are closely related to first-order periodicity rather than to second- or higher order periodicity, and hence it is necessary to discuss the feasibility of detecting first-order periodicity using cyclostationarity. Working on real helicopter data, we then show that some advantages of using cyclostationarity for helicopter signal detection are improvement of (cyclic) frequency resolution and enhancement of the probability of detection. For helicopter signals with time-variant Doppler shift, a cyclic frequency smoothing method is proposed. This method does not have a counterpart in communication applications, and should be useful for acoustic signal processing.

1 Introduction

Recently, the theory of cyclostationarity has received much attention because of its wide applications in diverse areas such as communications, hydrology, biology, economics, etc. [1]-[3]. In particular, significant progress has been made in exploiting cyclostationarity for a variety of manmade signals encountered in communications [1]-[3]. In line with the success of using cyclostationarity in communications, there is a tendency in applying the theory of cyclostationarity to process other type of signals such as acoustic signals (see e.g. [4]). However, few results are available in the literature which deal with helicopter acoustic signals using cyclostationarity. In this paper, we consider the practical problem of helicopter signal detection using cyclostationarity.

The extraction of helicopter signals was considered in [5], using an iterative method for maximizing a likelihood function. However, the additive noise in [5] has been assumed to be AR process. The extraction of almost periodic signals, which include helicopter signals, was discussed in [6] using cyclostationarity, where the noise has been assumed to be cyclostationary with zero mean or known non-zero mean. Further, the issue of Doppler shift effect was not taken into account in [6]. In practice, background noises could be highly nonstationary, such as acoustic signals radiated by vehicles passing near the acoustic sensors or other transient types of sound. In this paper, we present experimental results on helicopter signal detection using cyclostationarity without imposing any restriction on the additive noise.

In the next section, we show that helicopter acoustic signals are closely related to first-order periodicity and then discuss the general problem of detecting first-order periodicity using cyclostationarity. In Section 3, we consider the problem of using cyclostationarity to detect helicopter signals without and with time-variant Doppler shift effects. Finally, a summary is presented in Section 4.

2 Detection of First-order Periodicity

It is well known [1]-[3] that the theory of cyclostationarity is particularly useful for the analysis of second-order and higher-order periodical signals. Experiments with helicopter acoustic signals reveal that he-

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licopter signals are closely related to first-order periodicity rather than to second-order periodicity, because there exist harmonic spectral lines in the power spectral density (PSD) of a given helicopter signal. This finding also agrees with earlier works on helicopter signals [5][7]. It is then natural to ask whether the theory of cyclostationarity can play a role in the detection of first-order periodicity.

Let $s(t)$ be a simple first-order periodic signal, that is, a sinusoid $s(t) = \cos(2f_0t + \theta)$ and $S_s^\alpha(f)$ be its spectral correlation density function (SCD), then we have [3]:

$$S_s^\alpha(f) = \begin{cases} \frac{1}{4}\delta(f - f_0) + \frac{1}{4}\delta(f + f_0) & \text{for } \alpha = 0 \\ \frac{1}{4}e^{\pm j2\theta}\delta(f) & \text{for } \alpha = \pm 2f_0 \\ 0 & \text{otherwise} \end{cases}$$

on the principal domain.

It is easily seen that $S_s^\alpha(f) \not\equiv 0$ only along the α and f axes. However, no new information is gained in $|S_s^\alpha(0)|$ as compared with the PSD $S_s^0(f)$ because there exists a one to one correspondance between $S_s^0(f)$ and $|S_s^\alpha(0)|$. That is, an impulse at $f = f_0$ in $S_s^0(f)$ will also appear as a corresponding impulse at $\alpha = 2f_0$ in $|S_s^\alpha(0)|$ and vice versa. Therefore, theoretically, exploiting cyclostationarity offers no better result than conventional power spectral analysis for first-order periodic signals [1-3].

Nevertheless, in practice, when the data length of a first-order periodic signal to be processed is not long enough and the SNR is low, the estimation of $|S_s^\alpha(0)|$ may perform better than that of $S_s^0(f)$, as is shown in figures 1 and 2, where a sinusoid is mixed with an additive nonstationary noise. This motivates the study of helicopter signals by exploiting cyclostationarity, as will be discussed in the next section.

3 Detection of Helicopter Signals

Let $x(t)$ denote a helicopter acoustic signal mixed with a nonstationary additive noise and $S_x^\alpha(f)$ be its SCD. We shall first consider the case where the period of a helicopter signal is fixed, and then proceed to the case where time-variant Doppler shift is present.

3.1 Helicopter Signal with Fixed Period

When the SNR of $x(t)$ is high, a helicopter signal can be easily detected by inspecting $S_x^0(f)$ whether it contains harmonic spectral lines. However, when the SNR is low, the harmonic spectral lines in $S_x^0(f)$ may be hidden due to noises. In order to reduce the noisy effects, time-smoothing or frequency-smoothing is required, or equivalently, the product $\Delta t \Delta f \gg 1$, where Δt is the length of the data segment, and Δf is the frequency resolution [1].

In many cases, Δt is limited for practical reasons and hence Δf would have to be increase, leading to the reduction of frequency resolution. On the other hand, because fundamental frequencies of helicopter signals are rather low (typically between 10 to 30 Hz), higher frequency resolution is required in order to detect accurately the fundamental frequency of a helicopter signal. This difficulty may be overcome by using cyclostationarity. Specifically, because of the one to one correspondance between $S_s^0(f)$ and $|S_s^\alpha(0)|$ for a first-order periodic signal $s(t)$, we can check whether or not there exist harmonic spectral lines in $|S_x^\alpha(0)|$ where the cyclic frequency resolution $\Delta\alpha$ is on the order of $1/\Delta t \ll \Delta f$. Experimental results are shown in figures 3 and 4, which illustrate the superiority of $|S_x^\alpha(0)|$ over $S_x^0(f)$ with respect to (cyclic) frequency resolution.

In addition to improving cyclic frequency resolution, exploiting cyclostationarity may also enhance the probability of detecting weak helicopter signals, because we now have both $S_x^0(f)$ and $|S_x^\alpha(0)|$ to inspect whether or not there exist harmonic spectral lines.

3.2 Helicopter Signals with Time-variant Doppler Shift

In reality, it is more common to assume that the period of a helicopter signal under study is slowly varying due to time-variant Doppler shift effect. In such a case, we propose a modified method for detecting helicopter signals using cyclostationarity.

Cyclic frequency smoothing method: We process the noisy helicopter data in the same ways as in Section 3.1, except that $|S_x^\alpha(0)|$ is smoothed in α to reduce the time-variant Doppler shift effect:

$$\hat{S}_x^\alpha(0) = \frac{1}{M} \sum_{v=-(M-1)/2}^{(M-1)/2} |S_x^{\alpha+v\Delta\alpha}(0)|.$$

where M controls the amount of smoothing. The purpose of this cyclic frequency smoothing method is to give a better estimation of the averaged fundamental frequency for a given helicopter signal with slowly time-varying Doppler shift. Note that the cyclic frequency resolution has reduced from $\triangle\alpha$ to $M\triangle\alpha$ after cyclic frequency smoothing.

An illustrative example for the above method is presented in figures 5 and 6. Comparing figure 5 with figure 3, it can be easily seen that time-variant Doppler shift effect is present in figure 5 because the harmonic spectral lines have been broaden. After performing cyclic frequency smoothing, the effect of time-variant Doppler shift is reduced, as shown in figure 6.

Remarks: In communication applications, where the underlying period of a signals is usually fixed, there is no need to smooth the cyclic frequency α. It should also be pointed out that smoothing of $|S_x^\alpha(0)|$ in α is different from smoothing of $S_x^0(f)$ in f in the sense that frequency smoothing is mainly for noise reduction, while cyclic frequency smoothing is for reducing the effect of time-variant Doppler shift. Moreover, after cyclic frequency smoothing, the cyclic frequency resolution $M\triangle\alpha$ may still be higher than the frequency resolution $\triangle f$.

4 Conclusion

In summary, we have presented experimental results on real data for the detection of helicopter signal buried in nonstationary noises using cyclostationarity. It is shown that by exploiting cyclostationarity, the probability of detection can generally be improved, although not as drastically as in the application of cyclostationarity in communications. We have proposed a cyclic frequency smoothing method, which we believe to be useful for acoustic signal processing. Further comprehensive study on the applications of cyclostationarity in the processing of helicopter signals and other acoustic signals is needed.

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References

[1] W.A. Gardner, *Statistical Spectral Analysis: A Nonprobbilistic Theory*, Prentice-Hall, Englewood Cliffs, NJ, 1987.

[2] W.A. Gardner, "Exploitation of spectral redundancy in cyclostationary signals," *IEEE Signal Processing Magazine*, Vol. 8, No. 2, pp.14-36, April, 1991.

[3] W.A. Gardner, (Editor) *Cyclostationarity in Communications and Signal Processing*, IEEE Press, New York, 1994.

[4] P.J. Sherman, "Random processes from rotating machinery," in Proceedings of the Workshop on Nonstationary Stochactic Processes and Their Applications, Hampton, VA, 1-2 Aug. 1991, World Scientific, Singapore, 1992.

[5] M. Feder, "Parameter estimation and extraction of helicopter signals observed with a wide-band interference," *IEEE trans. Signal Processing* , Vol. 41, No. 1, pp. 232-244, Jan., 1993

[6] A. Dandawate and G. Giannakis, "Extraction of almost periodic signal using cyclostationarity," *Proc. IEEE ICASSP - 94*, Vol. IV, pp. 141-144, 1994.

[7] R.F. Dwyer, "Extraction of helicopter-radiated noise by frequency domain," *J. Acoust. Soc. Amer.*, Vol. 78, no. 1, pp. 95-99, 1985.

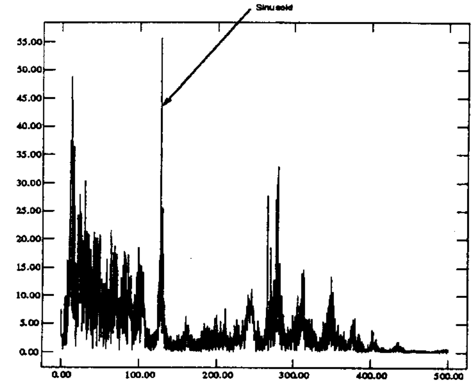

Figure 1: $|S_s^\alpha(0)|$ for $\cos(f_0 t)$ in noise

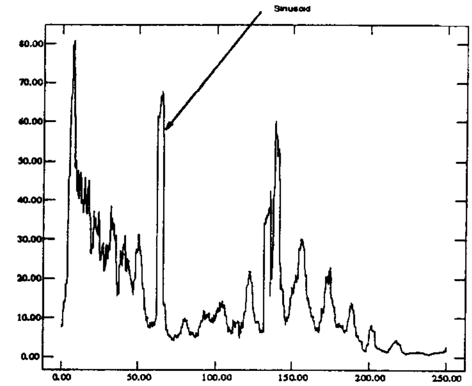

Figure 2: $S_s^0(f)$ for $\cos(f_0 t)$ in noise

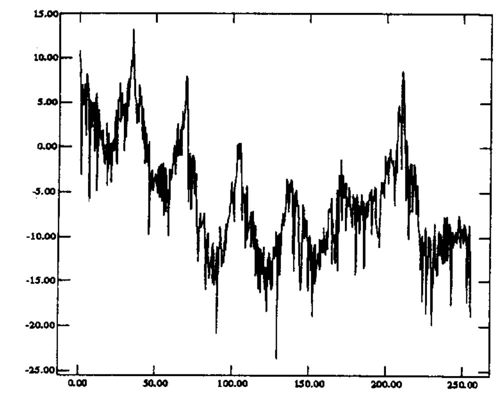

Figure 3: $|S_x^\alpha(0)|$ for noisy helicopter signal

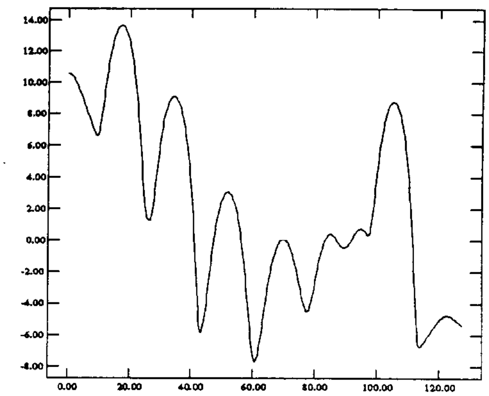

Figure 4: $S_x^0(f)$ for noisy helicopter signal

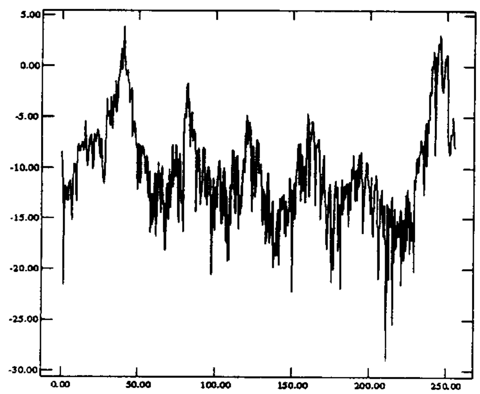

Figure 5: $|S_x^\alpha(0)|$ for noisy helicopter signal

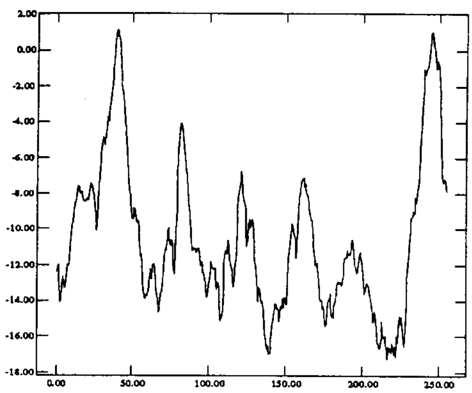

Figure 6: Smoothing of $|S_x^\alpha(0)|$ in α