Real-Time Separation of Periodic and Non-periodic Signal Components

Cristyn Magnus

December 2001

1 Introduction

This paper examines several criteria for separating periodic and non-periodic components from real-time signals. While this is similar to the more familiar issue of de-noising signals, it is different in that de-noising concerns itself with removing noise, such as tape hiss, from some original signal. The aim is to keep the original signal, including any noise it may contain, as intact as possible[3]. The criteria examined here attempt to extract all of the periodic components or all of the non-periodic components from some original signal that contains both. One can imagine many situations in electro-acoustic music in which it might be useful or interesting to present periodic or non-periodic components of a sound independently or process them independently[5].

2 Separation Method

2.1 Overview

In order to separate the components, the incoming signal must be analyzed and some criterion that distinguishes the periodic components from the non-periodic components must be established. This analysis involves applying overlapping windows with a length of N samples and a hop size of H to the time-domain input signal and transforming it into a frequency-domain signal using a Fast Fourier Transform. Each bin of the resulting spectrum is tested against some criterion that determines whether the bin will be multiplied by zero, removing its contribution to the resulting signal, or by 1, allowing its contribution to pass through to the resulting signal. This zeroing criterion is applied to each bin before taking the Inverse Fourier Transform. Finally, the extracted signal is reconstructed by windowed overlap add (figure 1)[4].

While the results of this approach can be perceptually convincing, the following caveat should be noted. Because the zeroing criterion applies to entire bins, if a bin contains information from both periodic and non-periodic components, the output will contain anomalies. The extracted non-periodic component will

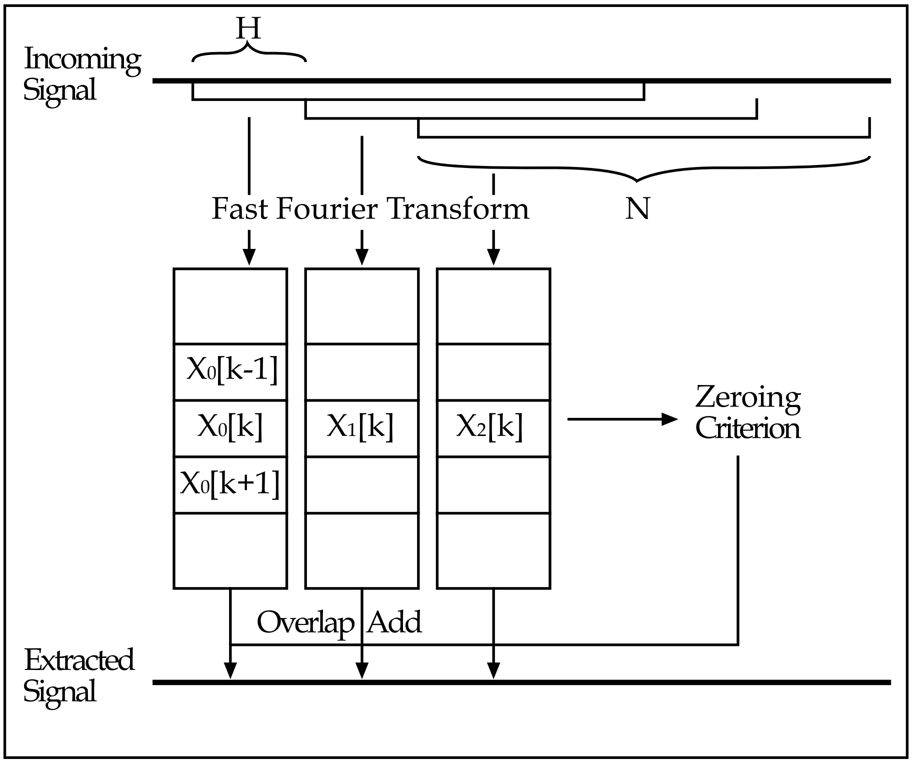

Figure 1: Diagram of Separation Method

have spectral gaps at bins classified as sinusoidal; the extracted periodic component will have noise added to its amplitude, causing it to waver slightly. In some cases, this is clearly perceptible, while in others these artifacts are surprisingly hard to hear.

2.2 Amplitude Criterion

The most effective methods of signal separation require some knowledge of at least one of the components. If we assume our non-periodic component is well modeled by white noise, we can design a criterion that capitalizes on the characteristics of noise. Because white noise has an evenly distributed spectrum and pure sinusoids are, at worst case, focused in a few bins, zeroing all bins with a magnitude less than some threshold r_a provides a simple, computationally inexpensive criterion for extracting the sinusoidal components (doing the opposite will extract the noise component.)[3].

With the complex amplitude of each bin $X[k]$ decomposed as

$$X[k] = A[k] + iB[k] \tag{1}$$

The amplitude criterion used is defined as

$$A[k]^2 + B[k]^2 \geq r_a \tag{2}$$

This method works quite robustly. However there are two obvious drawbacks. First, low amplitude periodic components, such as high partials, will be mis-classified as non-periodic components. This would result in a slightly pitched non-periodic component and a spectrally impoverished periodic component. Second, this method will fail when presented with a signal containing high-amplitude, spectrally-narrow, non-periodic component.

2.3 Stability Criteria

Stability criteria attempt to provide more versatility, allowing the process to be applied to signals of entirely unknown content—a desirable trait in a real-time system. These criteria simply look for signs of periodicity. One such sign is phase match between neighboring frequency bins. Because the windowing process results in a 180-degree phase shift for all phase angles[2], this is accomplished by checking that the neighboring bins are 180 degrees apart (figure 2), give or take some margin of error, r_p.

It follows from the law of cosines that

$$\cos^{-1}\Big(\frac{A[k]A[k+1] + B[k]B[k+1]}{|X[k]| \cdot |X[k+1]}\Big) \tag{3}$$

Average phase difference between a given bin, $X[k]$, and its two neighbors is

$$\begin{aligned}\overline{\Theta} = \frac{1}{2}\Bigg(&\cos^{-1}\Big(\frac{A[k]A[k+1] + B[k]B[k+1]}{|X[k]| \cdot |X[k+1]}\Big) + \\ &\cos^{-1}\Big(\frac{A[k]A[k-1] + B[k]B[k-1]}{|X[k]| \cdot |X[k-1]}\Big)\Bigg)\end{aligned} \tag{4}$$

Since $\cos(180) = -1$, the phase criterion can be defined as

$$\overline{\Theta} \geq r_p \tag{5}$$

Another sign is frequency stability. If a given bin has the same frequency, within some margin of error r_f, in neighboring windows, it can be assumed periodic[4].

If we define the frequency, $f(k)$, predicted by two bins as

$$F(k) = \frac{arg(\frac{X_1[k]}{X_0[k]})}{H} \tag{6}$$

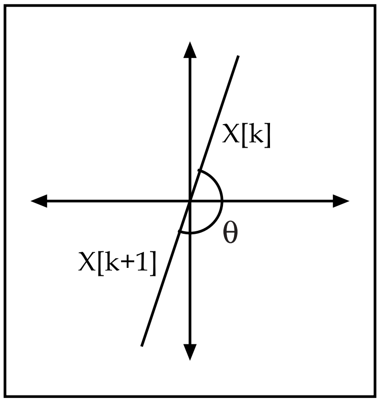

Figure 2: Phase relationship between bins with periodic components.

The frequency criterion is defined as

$$|F(k) - F'(k)| \leq r_f \tag{7}$$

Where $F'(k)$ is calculated in the same manner as $F(k)$, substituting $X_1[k]$ for $X_0[k]$ and $X_2[k]$ for $X_1[k]$.

3 Comparison of Crieria

3.1 Method

The three zeroing criteria were tested using a sample rate of 44.1kHz, a window size of N=2048, and a window overlap of 4. A subject was presented with a signal and asking that the subject set threshold and amplitude levels so that the non-periodic component was as high as possible, in relation to the periodic component, while still allowing the periodic component to be successfully extracted. The test signal was comprised of a sinusoid of random frequency and a non-periodic component, randomly selected from the following: white noise, non-flat broadband noise, band-limited noise of random frequency and Q, or an impulse train. For each iteration of the test, a different criterion was randomly selected and the threshold and amplitude levels were reset to prevent the previous iteration from biasing the next. The resultant amplitude, in decibels, of the periodic signal was then subtracted from the resultant amplitude of the non-periodic signal. This was used as the primary basis of comparison.

3.2 Results

Overall, the amplitude criterion outperformed both of the stability criteria (figure 3). This performance varied, though, depending on the type of non-periodic

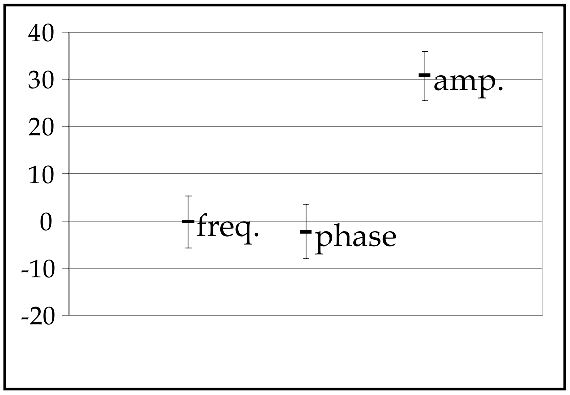

Figure 3: Overall Performance

sound. Both the white noise case and the non-flat noise case mirrored these results (figure 4–figure 5).

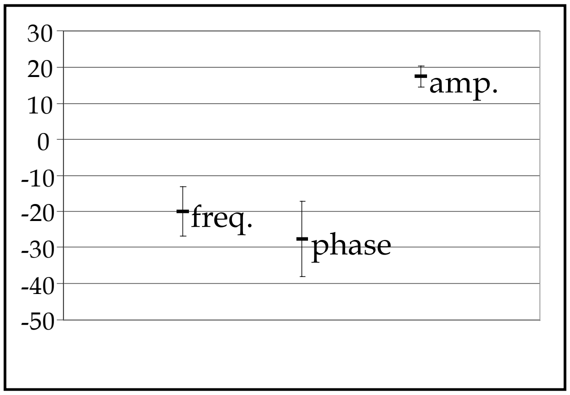

Figure 4: White Noise

Although the impulse case is the first one in which we see a significant difference between stability criteria, with the phase stability case performing slightly better than the frequency stability case, the amplitude criterion still proves to be superior (figure 6). The interesting case is the one in which the different criterion separate the periodic component from band-limited noise (figure 7). On first pass, it appeared that while the phase stability criterion performed significantly better than the frequency stability criterion, the amplitude criterion did not perform significantly differently from either of them because of its poor confidence rating. Upon closer scrutiny, its data set contained one point with a Q that was much smaller than the others. With this point dropped, the phase stability criterion was significantly better than the amplitude criterion at successfully separating the signals.

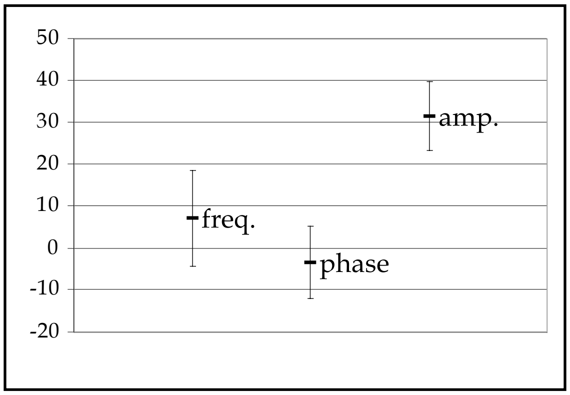

Figure 5: Non-Flat Noise

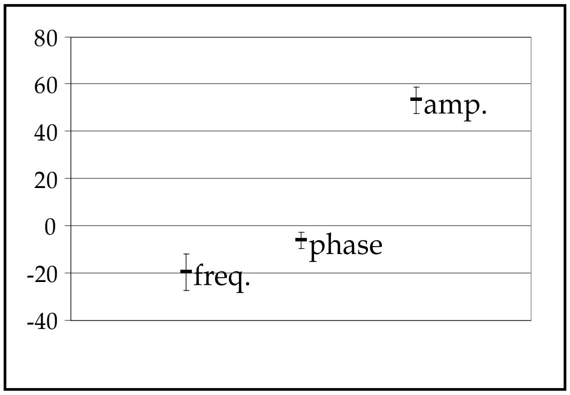

Figure 6: Impulse

4 Discussion

It is hard to draw a simple conclusion from these results. On one hand, the amplitude criterion appears to be a clear winner, but there is at least one situation, and possibly more, in which it fails dismally compared to the phase stability criterion. A hybrid of the two criteria should certainly be examined. Also, despite its poor performance, the frequency stability criterion shouldnt be completely abandoned. In this study, only two neighboring frequency estimates were used to test stability. Although more frequency estimates will introduce more latency, the results may make it worth experimenting with frequency estimates taken over a longer period of time.

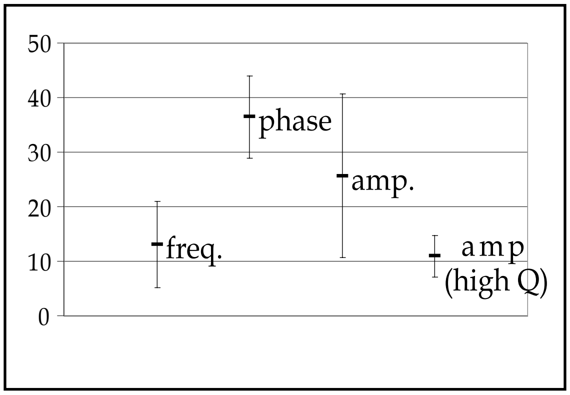

Figure 7: Band Limited Noise

Methods of testing various processes should also be further examined. There is a great deal of tension between the desire to test performance on real-world signals and the need to know what an incoming signal was initially composed of in order to assess a processs efficacy. Certainly the test cases in this study provided highly simplified and ideal situations. Since it is already clear that the amplitude criterion will produce excellent results when removing broadband noise, an attempt should be made to discover situations in which it will consistently fail so that methods that will succeed in those cases can be explored.

References

[1] M. Dolson. The phase vocoder: A tutorial. *Computer Music Journal*, 10(4):14–26, 1986.

[2] F. Harris. On the use of windows for harmonic analysis with the discrete fourier transform. *Proceedings of the IEEE*, 66(1):51–83, 1978.

[3] R. Hoeldrich. Real-time broadband noise reduction. *Proceedings ICMC98*, pages 150–156, 1998.

[4] M. S. Puckette, 2001. Personal communication.

[5] X. Serra. Musical sound modeling with sinusoids plus noise. http://www.iua.upf.es/ xserra/articles/msm, 1997.

[6] Z. Settel and C. Lippe. Real-time frequency-domain digital signal processing on the desktop. *Proceedings ICMC98*, pages 142–149, 1998.