SYNCHRONOUS SIGNAL REMOVAL VIA WAVELET PACKETS

Eric E. Keller¹, Eric R. Marsh¹, and Byron R. Knapp²
¹Department of Mechanical and Nuclear Engineering
The Pennsylvania State University
University Park, Pennsylvania, USA
²Professional Instruments
Hopkins, Minnesota, USA

INTRODUCTION

One of the fundamental signal processing techniques in spindle metrology is the separation of synchronous and asynchronous parts of spindle motion. While in many cases, the synchronous parts of the spindle motion are more important, there are many cases where knowledge of the asynchronous motion is desired. However, it is common that a time series describing the spindle motion is dominated by the synchronous motion. Applications involving vibration are one area where the desired signal is asynchronous to spindle motion.

Removal of synchronous (or harmonic) signals from a time series is a common problem in science and engineering. An example of this is removing the power line harmonics from low-level sensor signals. The literature regarding harmonic removal is extensive and spans many fields of study.

While standard methods[1] are quite reliable, the wavelet packet method presented here has some advantages. For example, the implementation presented here can be used to produce a time series that is limited to a single band of frequencies, for example to select particular a modal frequency. In addition, there is potential for on-line separation, although this has not been implemented.

WAVELET ANALYSIS

Wavelet analysis is conceptually similar to the Fourier Transform (FT). While it is common to think of the FT as transforming a signal into the frequency domain, it can also be considered as the process of decomposing the signal into frequency components. It is also a projection of the signal onto the frequency domain space. The latter two concepts make more sense in discussing wavelet analysis.

DISCRETE WAVELET TRANSFORM

The method discussed here is fundamentally an application of the discrete wavelet transform (DWT) or Multiresolution Analysis. The DWT is a well-known method of decomposing a signal in a way that preserves both time and frequency localization. The decomposition of a signal involves convolution of the signal with a wavelet, which is a short duration signal of finite energy. This allows a trade-off between preserving the time localization of a signal and the frequency localization of the signal. This contrasts with the Fourier transform, which determines frequencies present in a signal, but destroys the time localization unless extended methods such as the windowed Fourier transform are used.

At each level of decomposition, the DWT projects the signal into what are called the “Approximation” and “Detail” subspaces. The next level of decomposition further separates the approximations into details and approximations. Thus, the final level of decomposition, the signal is fully represented by the last coefficient of the approximation space at that level and the detail coefficients from the lower levels of decomposition. At each level of decomposition, the resulting coefficients are down-sampled by a factor of two. This results in a full decomposition having the same number of data points, only split into the coefficients of the resulting subspaces. Thus the method does not create or destroy information and is fully reversible without loss.

DISCRETE WAVELET TRANSFORM

The disadvantage of the DWT method is that the frequency bands that the signal can be decomposed into are limited to a dyadic structure, i.e. the frequencies have a power of two relationship with each other. This often results in a decomposition that is too granular for many applications. One method of solving this issue is the Wavelet Packet Decomposition (WPD). The WPD uses the same
decomposition as the DWT, but has flexibility in which subspaces of the signal that are decomposed. Thus it can be considered as recursively applying the DWT algorithm to subspaces of the original signal. Instead of decomposing only the approximation subspace at every level, the user has the choice of leaving the approximation coefficients as they are and decomposing the detail space. Just as with the DWT, the result of a WP decomposition is that there are still the same number of data points as the original signal, but they are split into a set of subspaces.

FILTERING USING WAVELET ANALYSIS

Since the DWT and WP project the original signal onto orthogonal subspaces, one trivial method of filtering is to simply zero out the coefficients of the decomposition that fall in a particular subspace. This removes that subspace from the space defined by the original signal. This is the main technique of bandpass filtering used in the work presented here. Typical applications of the DWT require some form of compression, and so this method is commonly used. It is good practice in sampled data systems to sample at a higher rate than the Nyquist criteria would suggest, and this means that there is no information content in much of the spectrum. This holds true in the wavelet domain as well.

BASELINE SHIFTING METHOD

In many cases, it is desirable to sample spindle motion data synchronized with the spindle rotation using an encoder. This is required for the method presented here to work. If the encoder has N counts, then the sampled data signal can have the synchronous data removed if the wavelet packet decomposition is performed to the $J = \log_2 N$. So for example, a 1024 line count encoder would result in a decomposition to the 10th level. This results in a single point in each coefficient for every complete revolution. Thus, the synchronous portion of the signal is removed by subtracting the average of these points over a number of cycles.

PROBLEMS WITH THE BASELINE SHIFTING METHOD

In real-world data, this fails to satisfactorily remove the synchronous data. The issue is that a sampled data system will spread the spectrum of the synchronous data. The baseline shifting method removes the data at exactly the harmonic frequencies, but leaves significant energy in the surrounding frequencies. In most applications, this is not particularly useful. This work incorporates a high pass filter at the terminal level of decomposition. This reduces the subspace of those terminal levels of decomposition, but there is no theoretical issue with using a time domain filtering technique on the coefficients at this level since they are fundamentally a time domain signal.

IMPLEMENTATION

The modified baseline shifting method was implemented using the Matlab programming language. A graphical user interface was constructed that displays the Fourier domain signal for both the original (red) and filtered (blue) signal. This allows the user to choose the wavelet and filter parameters and assess the results. It is convenient to look at the frequency domain results because it is possible to easily see the effect of the filtering. A comparison in the time domain is very difficult, particularly since this method is most useful in cases where the original signal is dominated by the synchronous element. Both lowpass and bandpass are possible with an option not to remove the synchronous signal which is mostly useful in the bandpass case.
FIGURE 2. The original signal from a grinding operation showing that the signal is dominated by the synchronous signal.

FIGURE 3. The filtered signal from the grinding operation showing the displacements with the synchronous signal removed.

EXAMPLE
An experiment with a rotary grinding operation was performed. The machine used is a Moore Nanotech CNC lathe with motorized Professional Instruments air bearing spindles for both the work and the grinding spindles. The work spindle is instrumented with four capacitance displacement gauges arrayed radially around the spindle. Thus, a grinding operation results in displacements of the work spindle. The work piece was a cylinder of tungsten carbide. Grinding was performed using a diamond grinding wheel. The setup is shown in Figure 2.

The work spindle is equipped with a 1024 count encoder, and the capacitance probe signals were sampled using the encoder input as a sample clock.

The experiment consisted of a touch-off pass, a cleanup pass and then a constant infeed grinding pass. The original signal is in Figure 2. Some evidence of the grinding operation is visible in the signal, but it is overwhelmed by the synchronous signal from the bearing end plate surface, which has a known defect. This signal was filtered using the Daubechies 5 wavelet retaining only the 11th coefficient. The 1024 encoder count means that the filtering occurs at the 10th level of wavelet decomposition.

The results of this filtering are shown in Figure 3. The results of the grinding operation can clearly be seen. These results are comparable to ad-hoc filtering techniques previously used.

CONCLUSIONS AND FUTURE WORK
The main advantage of this work is that it can be implemented as a recursive multi-time scale filter. This has not been implemented. Another issue is that wavelet analysis often has issues with transient distortion effects because they are equivalent to very high-order filters. There are methods to reduce these effects, which need to be explored further.

REFERENCES