Empirical Mode Decomposition of Micro-Doppler Signature

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ABSTRACT

Micro-Doppler induced by mechanical vibration or rotation of structures in a radar target is potentially useful for target detection, classification and recognition. In order to exploit the time-varying micro-Doppler signature, time frequency analysis techniques are used. However, they can not represent this useful information clearly all the time. In this paper, we introduce a novel algorithm to extract the micro-Doppler signature using a technique called empirical mode decomposition. Both simulation and the experimental results indicate that EMD provides us an effective way to give better time frequency representation of the micro-Doppler signature.

1. *INTRODUCTION*

In many cases, structures on the target may have vibrations or rotations in addition to target translation, such as a rotor on a helicopter, a rotating radar antenna on a ship or the swinging arms of a man. Mechanical vibration or rotation of structures in a radar target may induce additional frequency modulations on the returned radar signal which generate sidebands about the target's Doppler frequency, called the micro-Doppler effect. Analysis of the micro-Doppler signature can provide useful information for target detection, classification and recognition [1, 2].

These unique micro-Doppler signatures due to vibrating or rotating structures of the target are a function of time. Time frequency analysis methods are necessary to be used for such nonlinear and nonstationary signals [3]. However, these methods failed to reveal the micro-Doppler signature clearly when it is too weak.

This paper describes a new technique, called the empirical mode decomposition (EMD) that has been pioneered by N.E. Huang and al. for adaptively decomposing nonstationary signals as sums of zero-mean AM-FM components, called intrinsic mode functions (IMFs). Using this signal decomposition algorithm, the returns from the target body and the vibrating/rotating structures can be efficiently separated. Better target image will be obtained with reduction of the interferences from vibrating/rotating parts. On the other hand, micro-Doppler signature can also be revealed much clearer after the separation. In this paper, our attempt focused on the micro-Doppler signature representation. It helps us to detect some still target with vibration structures.

We take the micro-Doppler induced by vibration as example to testify the efficiency of EMD. Both simulation and the experimental signals are used to indicate that the novel method succeeds to extract the micro-Doppler and give better time frequency representation of it.

2. *EMPIRICAL MODE DECOMPOSITION*

Empirical Mode Decomposition (EMD) has been introduced by N.E. Huang et al. for nonlinear and nonstationary signal analysis [4]. The general idea of this method is the sifting process to decompose any given signal into its intrinsic oscillations. With the EMD approach, the basis functions themselves are nonlinear functions which can be derived directly from the data, or in other words, an adaptive basis called Intrinsic Mode Function (IMF) can be found.

Here IMF is a function that satisfies two conditions: (1) in the whole data set, the number of extrema and the number of zero crossings must either equal or differ at most by one; and (2) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. In the case a time series is $x(t)$, EMD has the following major steps:

Initialize $r_0(t) = x(t)$ and $i = 1$

Step1: Set $h_0(t) = r_{i-1}(t)$ and $j = 1$

Step2: Extract the local minima and maxima of time series $h_{j-1}(t)$. Interpolate the local maxima by a cubic spline to form upper envelope H_{up} of $h_{j-1}(t)$. And construct the lower envelope H_{low} of $h_{j-1}(t)$ by fitting all the local minima with cubic spline. The upper and lower envelopes should cover all the data between them.

Step3: We calculate the mean value of the envelopes by $m_{j-1}(t) = (H_{up} + H_{low})/2$. The difference between $h_{j-1}(t)$ and its mean is $h_j(t) = h_{j-1} - m_{j-1}$.

Step4: If $h_j(t)$ meets the criteria of an IMF, designate this $h_j(t)$ as $imf_i(t)$. If $h_j(t)$ is not an IMF, then increment j, return to step 2 and repeat the procedure. If the amplitude of $h_j(t)$ is smaller than 10^{-10} times of the amplitude of r_{i-1}, the sifting process will be artificially stopped.

Step5: Define the residue as $r_i(t) = r_{i-1}(t) - imf_i(t)$. If $r_i(t)$ meets the stop criteria, the whole sifting procedure should stop. If not, increment i and return to step 1. We set the final stop criterion to be that $r_i(t)$ has a predetermined number of extrema.

The essence of EMD is to identify the intrinsic oscillatory modes by their characteristic time scales in the data empirically, and then decompose the data accordingly. The decomposition bases, IMFs, are produced directly from the signal itself, so they are adaptive according to the signal intrinsic characteristics. And the decomposition components are more meaningful as they are identified by their physical nature. According to this novel characteristic, we hope to separate the return signals according to their different physical movements. Thus micro-Doppler signature is expected to be extracted from the main Doppler frequency.

2. *EMD ANALYSIS OF SIMULATED SIGNAL*

To test the performance of the presented method, a simulated micro-Doppler signal induced by vibration were firstly investigated in this section.

For the simplest case, we consider radar observing a scene that contains a point target vibrating along the line-of-sight at a distance d. Its vibration frequency is f_v and the amplitude of the vibration is A_v. So the distance between radar and target is

$$r(t) = d + A_v \sin(2\pi f_v t) \tag{1}$$

In the case that the reflective frequency corresponding to a stationary pixel of the target is f_d and the reflectivity of the point target is ρ, the received radar signal from target becomes

$$S(t) = \rho \, e^{j[2\pi f_d t + 4\pi \frac{r(t)}{\lambda_c}]} = \rho \, e^{j[2\pi f_d t + \phi(t)]} \tag{2}$$

The phase function

$$\begin{aligned}\phi(t) &= \frac{4\pi d}{\lambda_c} + \frac{4\pi A_v}{\lambda_c}\sin(2\pi f_v t) \\ &= \phi_0 + \phi_1 \sin(2\pi f_v t)\end{aligned} \tag{3}$$

We assume $A_v << \lambda_c$; thus $\phi_1 << 1$. Then the corresponding phasor is

$$\begin{aligned}e^{j\phi(t)} &= e^{j\phi_0} e^{j\phi_1 \sin(2\pi f_v t)} \\ &\cong e^{j\phi_0}[1 + j\phi_0 \sin(2\pi f_v t)] \\ &= e^{j\phi_0}[1 + \frac{\phi_0}{2}(e^{j2\pi f_v t} - e^{-j2\pi f_v t})]\end{aligned} \tag{4}$$

According to Function (2), the phasor corresponding to the vibrating target is

$$\begin{aligned}e^{j\phi_{dop}} &= e^{j2\pi f_d t} e^{j\phi(t)} \\ &= e^{j2\pi f_d t} + e^{j\phi_0}\frac{\phi_1}{2}(e^{j2\pi t(f_d + f_v)} - e^{j2\pi t(f_d - f_v)})\end{aligned} \tag{5}$$

In the time frequency representation, the reflective frequency will appear in three locations: the main target Doppler still appears at the correct location, while the micro-Doppler frequency will appear in each of two pixels separated by f_v in Doppler frequency. The two additional returns are known as paired echoes [5].

In our simulation, we assume the target is stationary while a point target of it is vibrating at $f_v = 20Hz$ with vibration amplitude $A_v = 0.1cm$. Radar is located in a distance of $15m$ to the target, operating at $1.5GHz$. The spectrogram of this simulated signal is shown in figure 1. The micro-Doppler signature lies at $\pm 20Hz$ as expected.

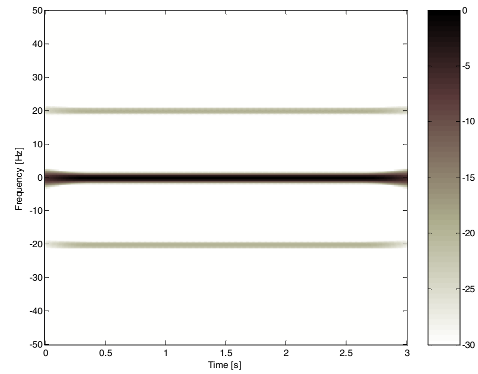

Figure 1 spectrogram of the simulated signal reflected from a vibrating point target

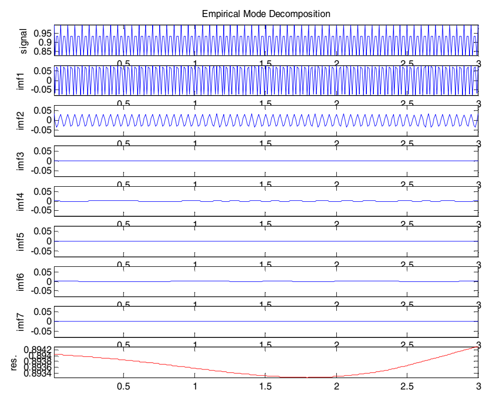

Figure 2 IMFs and residue obtained from EMD, compared with the original simulated signal

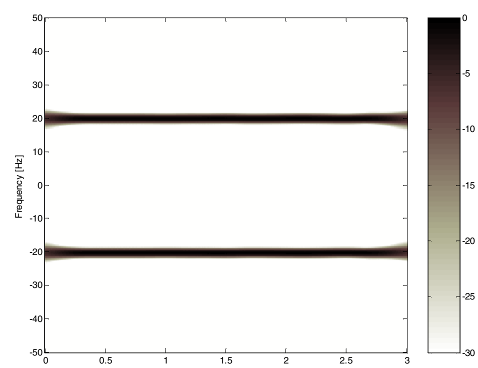

Figure 3 spectrogram of the extracted IMF2 from the simulated signal

Figure 2 shows the decomposition results. After the empirical mode decomposition, signal is divided into seven IMFs and the residue. After representing them in the frequency domain respectively, we found that IMF2 captures the micro-Doppler signature. The spectrogram of IMF2 is shown in figure 3. The vibration frequency is greatly emphasized by abandoning other unnecessary components.

3. *EMD ANALYSIS OF EXPERIMENTAL SIGNAL*

In this section, we try to use this new algorithm in a practical application. The real signals are reflected from a stationary truck with its engine on. The radar antenna is located 10 meters away, pointing towards the truck compartment (figure 4). EMD is applied to help detect the truck by revealing the micro-Doppler signature in the time frequency domain.

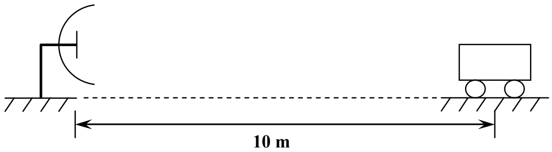

Figure 4 Real signals returned from a truck with engine on

We selected several carrier frequencies from $100MHz$ to $900MHz$. All the reflected signals using small carrier frequencies showed clearly the micro-Doppler signature at around $\pm 30Hz$. However the results of big carrier frequencies failed to display clear micro-Doppler signature. For example, when the carrier frequency is $563MHz$, the spectral of the returned signal is shown in figure 5. In addition to the micro-Doppler frequency, there are many harmonics which make it too confused to distinguish the micro-Doppler frequency.

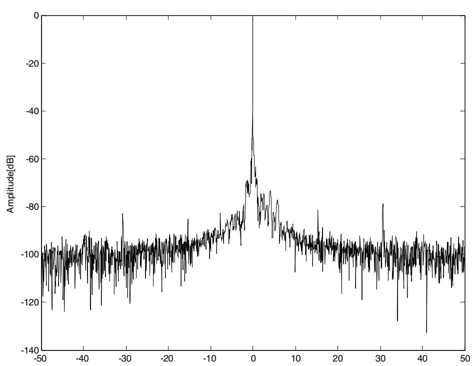

Figure 5 Fourier spectral of a returned signal whose transmitted microwave frequency is $563MHz$.

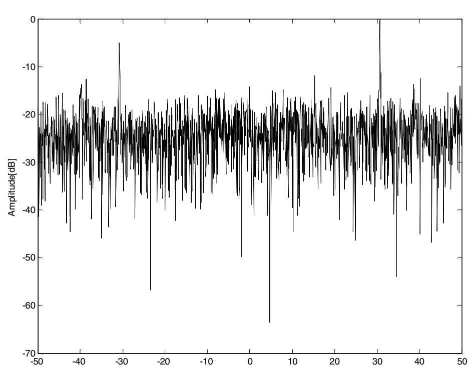

Figure 6 Spectral of IMF1 obtained after EMD of $563MHz$ signal

After EMD, the original signal is divided into one IMF and the residue. We noticed that the lowest frequency is kept out by the second IMF, so we can easily reduce the zero-Doppler components by eliminating this mode from the signal. The spectral of the left IMF1 is given in figure 6. We can see that after removing the IMF2, micro-Doppler gains the peak energy. The EMD result is given in figure 7.

We apply the short time Fourier transform on original $563MHz$ signal and the decomposed IMF1, respectively. Figure 8 representing the spectrogram of original signal, shows big energy of zero-Doppler, as a result the lowest frequencies coming from relatively motionless environment and the truck itself is the majority returned signal. There are several paired lines expect for the micro-Doppler frequency. We can hardly tell which one is the information we need.

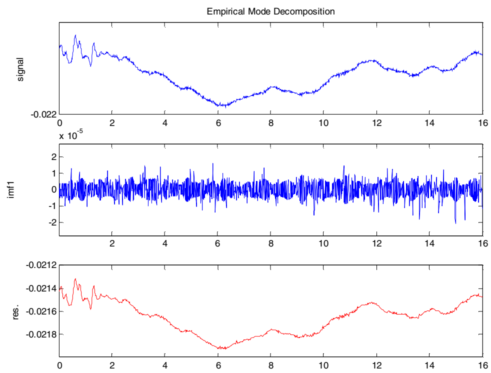

Figure 7 EMD result of the $563MHz$ signal

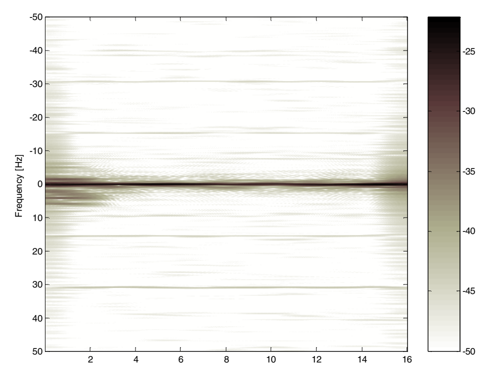

Figure 8 Spectrogram of the $563MHz$ micro-Doppler signal

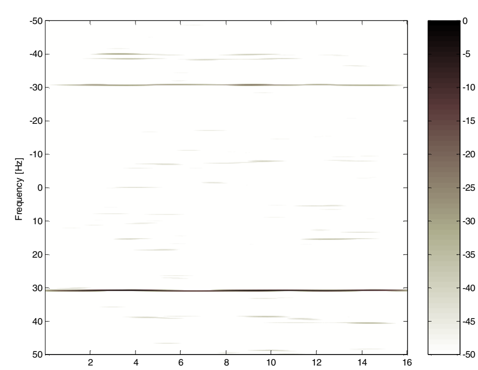

Figure 9 Spectrogram of IMF1 of $563MHz$ micro-Doppler signal

As expected, after EMD, the spectrogram of IMF1 shows clearly the micro-Doppler signature in the time-frequency domain as shown in figure 9. Disciplinary vibration of the truck engine caused micro-Doppler spreading symmetrically at $\pm 30Hz$.

We use another case to further test the efficiency of this method. It's a signal reflected from the same situation but the transmitted frequency changes to $802MHz$. Thus the disturbances from environment become severer and make the detection of engine vibration more difficult.

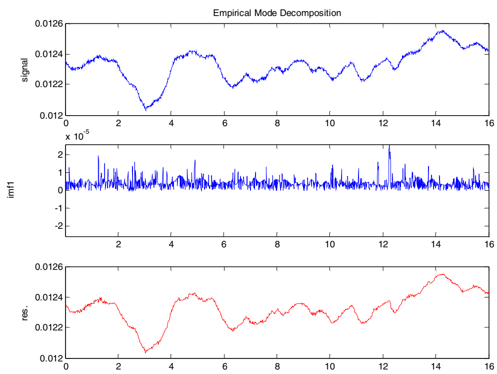

Figure 10 EMD result of the $802MHz$ signal

After EMD, as in figure 10, the signal is decomposed into one IMF and the residue. We discard the residue as it contains lowest frequencies of the original signal.

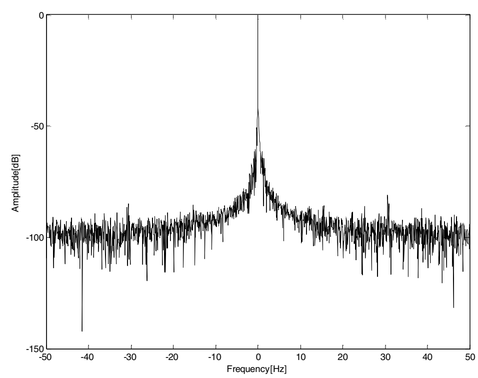

Figure 11 Fourier spectral of $802MHz$ signal

Figure 11 and 12 represent the Fourier spectral of original $802MHz$ signal and the IMF1 separately. It's clear that the micro-Doppler frequency energy is greatly emphasized after EMD.

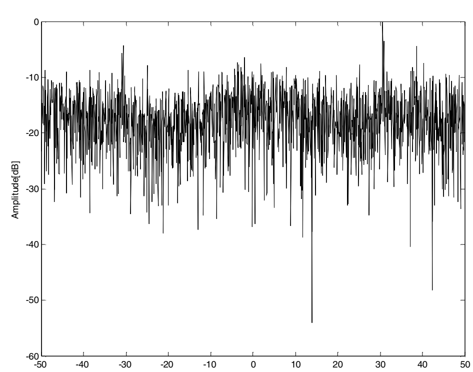

Figure 12 Fourier spectral of IMF1 of the $802MHz$ signal

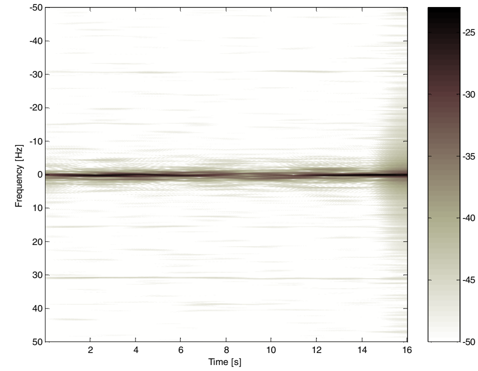

Figure 13 Spectrogram of the $802MHz$ signal

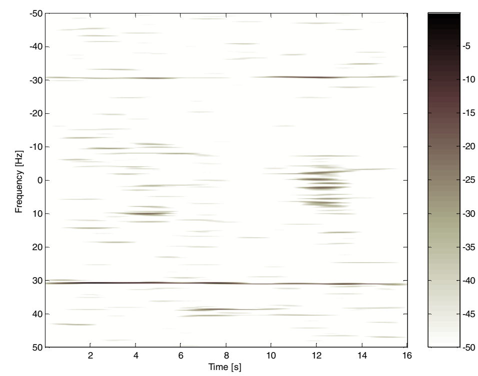

Figure 14 Spectrogram of IMF1 of $802MHz$ signal

The spectrogram comparison of original signal and the correlative IMF1 are given in figure 13 and 14 respectively. For the original signal, we try to suppress the zero-Doppler energy simply by subtracting its mean value. Although it's helpful, the micro-Doppler spreading is still very weak in the time-frequency domain. With the help of EMD, micro-Doppler can be seen in the spectrogram of IMF1. The micro-Doppler is basically separated from other interferences, clearly showing the sign of moving target. It's very valuable for detecting the vehicles no matter it is moving or not.

This analysis demonstrates once again the efficiency of the proposed method in decomposing the signal adaptively.

4. *CONCLUSION*

By exploiting the unique micro-Doppler signature of the target, we can get additional information that is complementary to existing methods. However micro-Doppler is usually very weak so that it is hard to be detected by traditional time frequency analysis methods. In this work, we have proposed a new methodology, EMD, to decompose a signal into different oscillatory modes and to extract the micro-Doppler signature. Since the empirical mode decomposition is based on the local characteristic time scale of the data, it has more physical meaningful interpretation. Separated according to the intrinsic oscillations, micro-Doppler reflected from the vibrating target can be extracted and represented in the time-frequency domain clearly.

Applied to simulated and experimental signals, the EMD allows us to display the micro-Doppler signature clearly while it's contaminated with interference and the main echoes from target body. EMD is validated to be efficiency for the vehicle detection even it's not moving.

5. *REFERENCES*

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