Modified HHT Analysis of Micro-Doppler Signatures Scattered from Rotating Flat Blades

#Ji-Hoon Park [1], Ik-Hwan Choi [2], Noh-Hoon Myung [1]
[1]Department of Electrical Engineering
Korea Advanced Institute of Science and Technology (KAIST)
373-1, Guseong-Dong, Yuseong-Gu, Daejeon 305-701, Korea, dydynoel@kaist.ac.kr
[2]Agency for Defense Development (ADD)
POB 305-5 Yuseong Post Office, Yuseong-Gu, Daejeon, Korea

1. Introduction

When a small reconnaissance aircraft with small radar cross section (RCS) is observed by radar, a micro-Doppler signature from its rotating propeller can be importantly used for target recognition. For extracting the feature of the target, a time-frequency analysis (TFA) is adopted as a representative method to explain the micro-Doppler characteristic. In recent years, the TFA has been applied to the various micro-Doppler signatures backscattered from rotating targets such as a helicopter rotor [1-2] and a jet engine turbine [3]. It is recommended that time-frequency transforms with higher time-frequency resolution should be employed in order to obtain more accurate and discriminative TFA results. From that point of view, Hilbert-Huang Transform (HHT) can be a good choice for analyzing micro-Doppler signatures because of its high-resolution characteristic.

In this paper, we use the scattered field data obtained from the propeller modelled as multiple rotating metal flat blades [4-5]. The scattered field data was calculated based on geometrical optics (GO) and equivalent currents method (ECM). The TFA results of the micro-Doppler signatures are then presented by applying the modified form of the HHT to the data.

2. Analysis Model and Scattered Field Calculation

For the analysis of the scattering from the rotating propeller, it was modelled as multiple flat blades [4-5]. As illustrated in Fig. 1, a metal flat blade with the size of L_1 x L_2 and the skew angle φ_s rotates along y-axis (rotation on x-z plane) with an angular speed $\theta_s = \omega t$. Due to the fact that the angular frequency ω and the rotation speed are much less than the radar frequency and the speed of the light respectively, the quasi-stationary approach can be used for the analysis of the micro-Doppler signature from rotating blades. The scattered field was calculated based on GO and ECM. For an incident plane wave, the ECM was employed to calculate an equivalent current on each edge of the blade. The line integral was then applied to obtain the scattered field by the blade. Detailed procedures are described in [4-5].

In many cases, small aircrafts have propellers with more than two skewed blades. Therefore, it is required that the model described in Fig. 1 should be extended to the propeller model with multiple blades for considering practical problems. Fig. 2 shows the extended analysis models with different number of the blades. Scattered field can be simply calculated with the superposition principle and the phase difference factor for each edge. The scattered field data from the analysis method and models explained above are regarded as the micro-Doppler signatures generated by the rotating blades. In the next section, the TFA is performed for these signatures obtained in [5].

3. Time-Frequency Analysis with Modified HHT

3.1 Modified HHT

HHT was first proposed by N. E. Huang for analyzing non-stationary and non-linear signatures [6]. It is composed of two consecutive steps: empirical mode decomposition (EMD) and Hilbert spectral analysis (HSA). The EMD decomposes a target signature into a finite number of intrinsic mode functions (IMFs) on the assumption that any data set consists of intrinsic modes of oscillation. Therefore, each extracted IMF denotes each oscillatory mode included in a raw signature and is expected to have a narrow-band component. The HSA forms an analytic signature with the combination of the IMF and its Hilbert transform. Then an instantaneous frequency defined in (1) can be extracted from the instantaneous phase of the analytic signature.

$$f_i(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt}. \tag{1}$$

Here, t denotes time and $\Phi(t)$ is the instantaneous phase derived from the analytic signature. The HSA finally shows the instantaneous frequency in the 3D time-frequency-amplitude plot, which is called Hilbert spectrum. The definition in (1) can be valid when the analyzed signature is narrow-band and thus (1) cannot be applied to most practical cases. The HHT, however, makes the definition clear by narrow-band IMFs extracted from the EMD. Therefore, the HHT can have much higher resolution than other time-frequency transforms in the analysis of time-varying micro-Doppler signatures.

Although the HHT can be considered as a promising tool for analyzing the micro-Doppler signatures, its several deficiencies originating from the EMD have been found and discussed. When the EMD occasionally fails to decompose the raw signature into the narrow-band IMFs, the characteristic of a signature cannot be interpretable. If the signature has numerous harmonics like the micro-Doppler signatures analyzed in this paper, there can be every possibility that each IMF has multiple frequency components. To prevent the EMD from decomposing the signature improperly, a variety of supplementary methods have been investigated such as a pre-processing filter [7]. In this paper, the modified HHT developed in [3] is employed for analyzing the micro-Doppler signature from rotating flat blades. The modified HHT adopts Meyer wavelet decomposition (WD) as a supplementary pre-processor. The WD basically divides the signature into a half low-band component and a half high-band component. Since the Meyer WD limits the frequency band to the first harmonic frequency, the possibility of the EMD failure can be reduced significantly. The WD level, M indicating the number of wavelet decompositions is given by

$$M = \left\lfloor \log\left(\frac{f_s}{f_1}\right) / \log 2 \right\rfloor, \tag{2}$$

where f_1 is the first harmonic frequency obtained from spectral analysis and f_s is the sampling frequency or the pulse repetition frequency (PRF) of the radar signature with a positive range. The modified HHT is expected to have the high-resolution characteristic of the original HHT and allow the IMF to characterize the micro-Doppler signature more correctly. The analyzed IMF corresponds to the first harmonic frequency, main interest in the micro-Doppler signature with harmonics.

3.2 Analysis Results

To analyze the micro-Doppler signatures from rotating blades, the modified HHT is applied to the scattered field data described in Section 2. Summarized information on the simulation parameters is given in Table 1. Hilbert spectrums in Fig. 3 show the instantaneous Doppler frequencies by different number of blades. Since the blades have finite skew angles, the time period of the instantaneous Doppler frequency is expressed by [4]

$$T = \frac{1}{N \cdot f_r}. \tag{3}$$

From (3), the time period of the instantaneous Doppler frequency turns out to be inversely proportional to the number of the blade and the rotation frequency. For example, if the period is 0.05 s in the 2-blade case, the period becomes 0.025 s in the 4-blade case. The TFA results from the modified HHT show not only good agreement with real number of the blades but also sinusoidally varying characteristics of the micro-Doppler signatures generated from rotating objects [8].

4. Conclusion

This paper has presented the TFA of the micro-Doppler signatures scattered from rotating flat blades using the modified HHT. After the modified HHT examined the scattered field data, the analysis results showed good agreement with real blade numbers in the propeller. It can be concluded that the TFA via the modified HHT provides the discriminative characteristic for recognizing a small aircraft target that generally has small RCS.

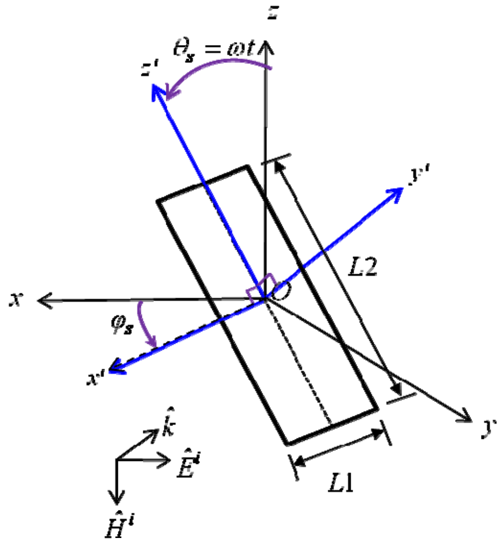

Figure 1: A Propeller Blade Modelled as a Metal Flat Blade

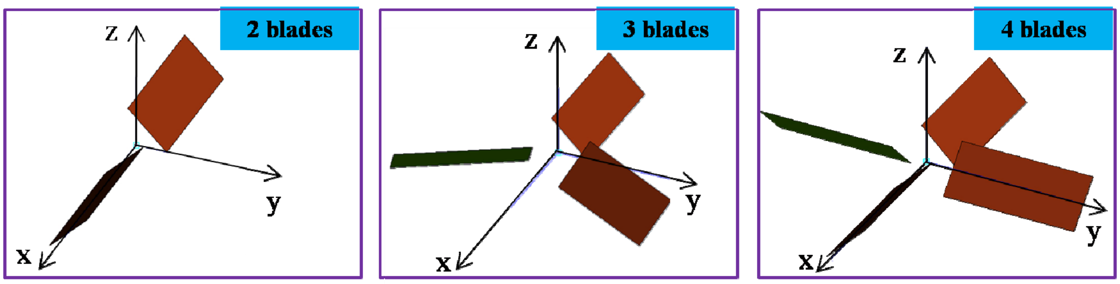

Figure 2: Extended Analysis Models with Multiple Blades

Table 1: Simulation Parameters

radar frequency	300 MHz
number of samples per sec.	3600
incident angle (φ, θ)	20°, 0°
skew angle (φ_s)	10°
rotation frequency (f_r)	10 Hz (600 rpm)
size of blade (L_1, L_2)	5λ, 2λ
number of blades (N)	2, 3, 4

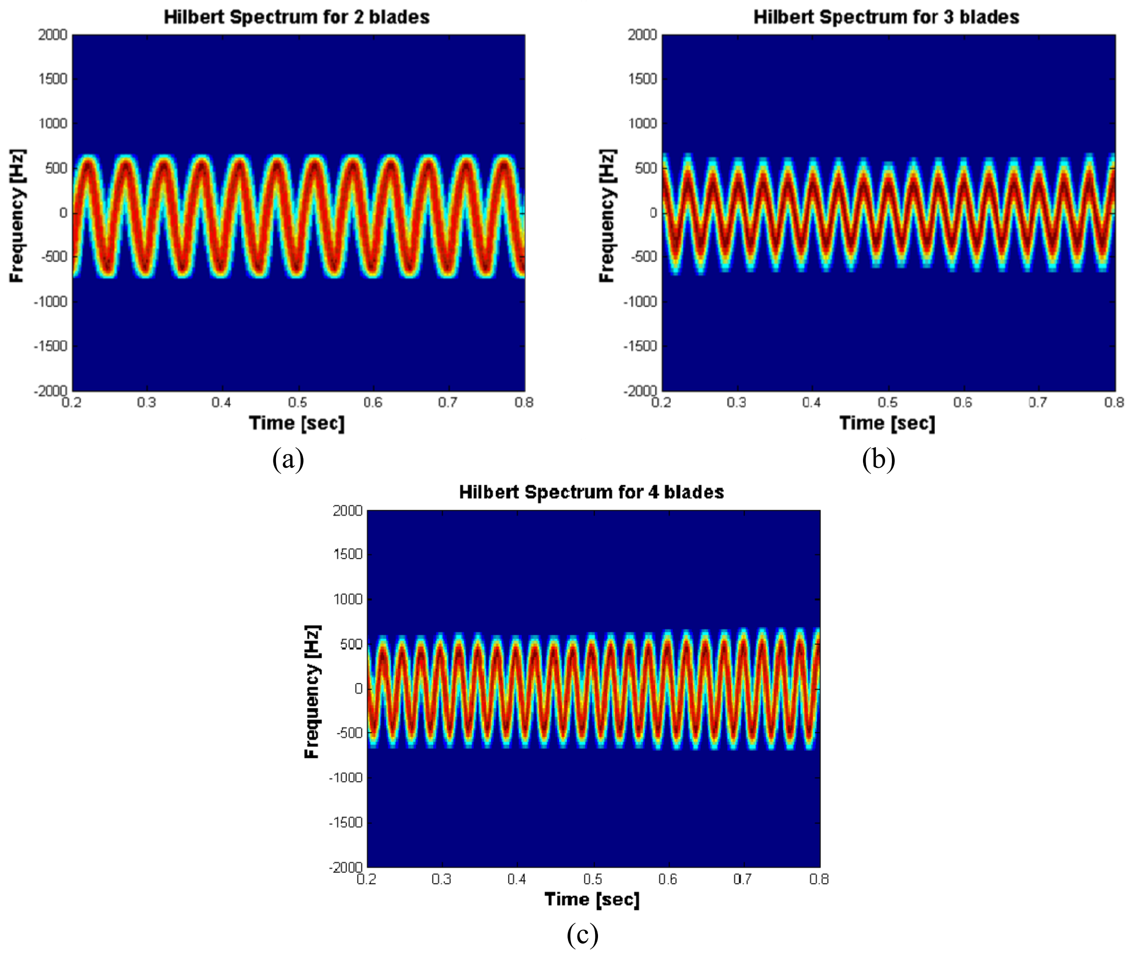

Figure 3: Hilbert Spectrums of the Micro-Doppler Signatures from Propeller with (a) 2 blades (b) 3 blades (c) 4 blades

References

[1] S. H. Yoon, B. W. Kim, Y. S. Kim, "Helicopter classification using time-frequency analysis," *IEE Electron. Lett.*, vol. 36, pp. 1871-1872, Oct. 2000.

[2] P. Pouliguen, L. Lucas, F. Muller, S. Quete, C. Terret, "Calculation and analysis of electromagnetic scattering by helicopter rotating blades," *IEEE Trans. Antennas and Propagat.*, vol. 50, pp. 1396-1408, Oct. 2002.

[3] J. H. Park, H. Lim, N. H. Myung, "Modified Hilbert-Huang transform and its application to measured micro Doppler signatures from realistic jet engine models," *Progress in Electromagnetic Research (PIER)*, vol. 126, pp. 255-268, Mar. 2012.

[4] Y. S. Sun, N. H. Myung, "Analysis of electromagnetic scattering by a rotating rotor with flat blades," *Singapore ICCS '94*, Singapore, Nov. 1994.

[5] I. H. Choi, H. Lim, D. W. Seo, K. U. Bae, N. H. Myung, "Analysis of electromagnetic backscattering from rotational flat blades," *2010 International Symposium on Antennas and Propagation*, China, Nov. 2010.

[6] N. E. Huang, Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N. C. Yen, C. C. Tung, H. H. Liu, "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis," *Proc. R. Soc. A*, Vol. 454, pp. 679-699, 1998.

[7] W. Yang, "Interpretation of mechanical signals using an improved Hilbert-Huang transform," *Mechanical Systems and Signal Processing 22*, pp. 1061-1071, 2008.

[8] V. C. Chen, H. Ling, *Time-frequency Transforms for Radar imaging and Signal Analysis*, Boston, MA, Artech House, pp. 181-190, 2002.