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Target Classification from JEM Signal Using Frequency Masking

Si-Ho Kim*, Chan-Hong Kim, Dae-Young Chae, and Sang-In Lee

Abstract—This paper deals with a technique for classifying jet aircrafts from JEM (Jet Engine Modulation) signal. A novel method to recognize an engine model by analyzing JEM spectrum using frequency mask is proposed. The frequency mask extracts and analyses the spectral component at the frequencies that are predicted from the blade number of a jet engine and the estimated spool rate. The proposed method does not need a complicated logical algorithm for finding the chopping frequency or the pre-simulated engine spectra used in previous methods. In addition, we suggest a method to precisely estimate the spool rate in the spectrum domain of JEM signal, which plays an important role in generating the frequency mask. The classification experiments using the JEM signals measured from two fabricated engine models verify that the proposed algorithm has good performance in the recognition of jet aircrafts.

1. INTRODUCTION

Radar is an electromagnetic system for the detection and location of target objects by transmitting an electromagnetic wave into space and receiving the reflected signal [1]. The reflected signal from a target has phase information as well as amplitude and they can be used for target classification. JEM target classification is the technology that classifies the class or type of jet aircraft by analyzing the reflected radar signal that is modulated by the rotation of blades in the jet engine of aircraft [2–12]. JEM scheme is known as the most practical method in the view point of computation load and performance in operational environment. The general approach in JEM scheme estimates the number of blades of jet engine using JEM signal and classify the target by comparing it with the number of blades of each engine in DB [2]. Only the blade number information is needed for classification and it is independent of aspect angle and frequency. Nonetheless, since the number of blade is principally integer value, it is hard to express similarity or degree of closeness for the result of classification. It means that target classification fails if the number of blade is not exactly estimated. The misestimation of blade number results from the incorrect estimation of spool rate and chopping frequency. The spool rate is the basic rotation rate of a jet engine compressor and the chopping frequency is the fundamental frequency of harmonics generated by the rotor blades of individual stages. It is important to estimate the spool rate and the chopping frequency from JEM signal. Especially, a complicated logical algorithm is needed to determine the fundamental chopping frequency among many spectral lines [3–5]. Alternative approach classifies a target by comparing the spectrum of measured signal and the spectra database for various known engines [6]. The latter would show better performance but it depends on the quality of the simulated spectra. Most of all, it is practically not easy to obtain the JEM spectra for various aspect angles and engines because the physical structure of engines as well as the number of blades are need to simulate them. To overcome the weakness of the two JEM schemes previously stated, we propose a novel scheme that can efficiently classify a target just using the blade number information without the complex logical algorithm to find the chopping frequency or the simulated spectra DB.

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* Corresponding author: Si-Ho Kim (sihokim@add.re.kr).
The authors are with the Agency for Defense Development, Daejeon, Korea.

2. TARGET CLASSIFICATION FROM JEM SIGNAL

A jet engine has a number of individual stages at its front and the different numbers of rotor blades on each rotor stage. The rotor blades are attached to a shaft for air compression as shown in Figure 1. Rotation of the rotor blades causes the complicated amplitude and phase modulation in the reflected radar signal. It is a hard problem to mathematically analyze and model the modulation property that has complex scattering mechanism including multiple reflections through many rotor stages. However, by analyzing the periodicity and symmetry of the effects and extracting the important features, target classification can be possible [2, 7]. The reflection property of engine blades repeats every rotation of shaft and its periodicity appears as the spool rate and its multiple harmonics in JEM spectrum.

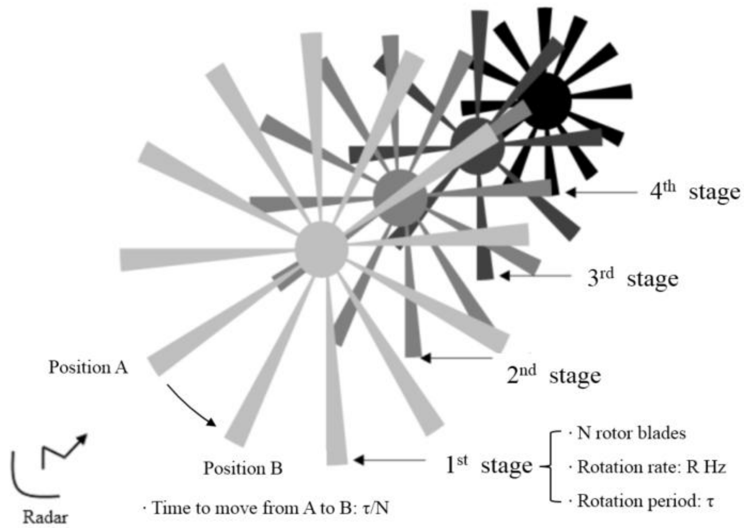

Figure 1. Simplified multiple rotor stages and blades of a jet engine.

Analyzing the reflection property in individual stages separately, the blades in a certain stage have symmetry, so the reflection property repeats whenever a single blade passes by the position of its neighbor blade in rotation. As shown in Figure 1, when the blade in position A moves to position B, the same reflection property appears repeatedly due to its symmetry so we can see the periodicity in the reflected signal. If the rotation period of the rotor is τ and the number of blades is N, the time interval moving between two blades become τ/N. We call the rate of this period as chopping frequency in the stage. Consequently, the mathematical relationship between the spool rate and the chopping frequency in each stage can be expressed as follows:

$$choppingFrequency = N \cdot spoolRate \tag{1}$$

Equation (1) implies that the number of blades in a rotor stage can be estimated by extracting the spool rate and the chopping frequency of the stage from JEM spectrum. In general, jet engines have the different number of blades in each rotor stage so the blade number information in each stage can be used for engine classification.

Figure 2 shows the simplified version of a typical JEM spectrum. The spectral lines that are arranged densely in the figure are the spool rate and its multiple harmonics. The relatively sparse and tall spectral lines in the middle are the chopping frequency and their harmonics for each stage. The ratio of the spool rate and the chopping frequency corresponds to the number of blades so theoretically it should be an integer but usually it is not because of estimation error. To get an integer value, round-off is useful if the estimation error is small. However, if the estimation error of the spool rate exceeds the maximum round-off error, 0.5, the estimated blade number is not correct. For example, when the actual number of blades is 50 and the estimation error of the spool rate is over 1%, then the estimated number of blades become 49 or 51 not 50. It means that the performance for estimating the number

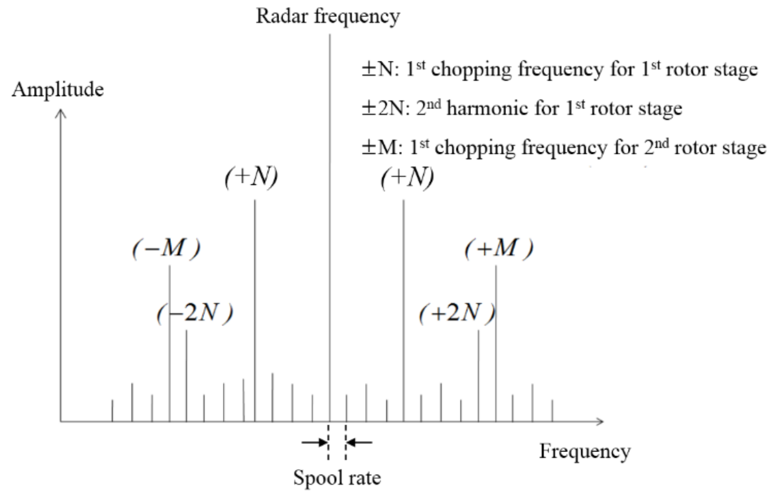

Figure 2. Typical JEM spectrum.

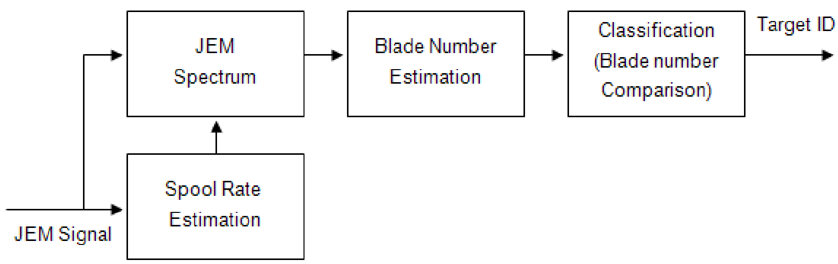

Figure 3. Target classification using JEM signal.

of blades highly depends on the accuracy of the estimated spool rate. In addition, it is more difficult and complicated to estimate the chopping frequency. The largest spectral line in JEM spectrum has the highest possibility to be the chopping frequency of first rotor stage but it is not always. It can be the multiple of the fundamental chopping frequency or the frequency component added or subtracted by inter-modulation between stages. Therefore, the logical algorithm to choose the correct chopping frequency among the harmonic lines is required but is usually complicated and complex. Even though the algorithm is optimized for a given signal DB, it cannot guarantee its performance for the other signals besides it.

Figure 3 illustrates the block diagram of the JEM classification system explained so far. In the figure, the JEM spectrum can be obtained from the Fourier transform of JEM time signal. The spectral lines in the spectrum are transformed to the blade number domain by dividing the frequency by the estimated spool rate and rounding it off to whole number. Then the number of blades is estimated by analyzing the spectral lines using the logical algorithm. Finally, the estimated number of blades is compared with that of the engine DB and the target is classified.

3. JEM TARGET CLASSIFICATION WITH FREQUENCY MASKING

3.1. Proposed JEM Target Classification System

In this section, we present our proposed system to classify a target by analyzing the JEM spectrum using frequency mask. If the blade number of an engine and the spool rate are given, we can predict the chopping frequencies and their harmonics. It means that we can classify a target by analyzing the total quantity of spectral components at the predicted frequencies for candidate engines in a given DB.

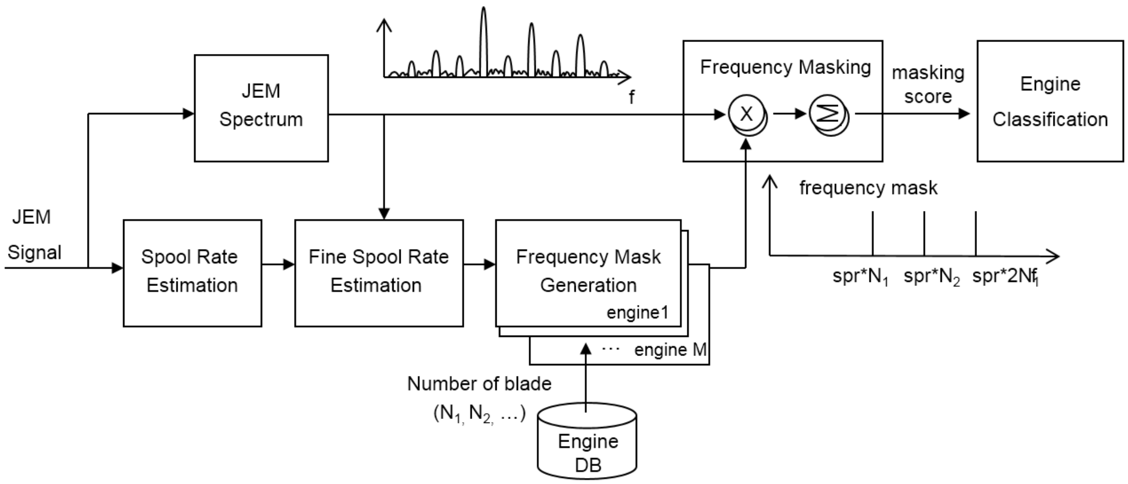

Figure 4. Proposed target classification system using frequency mask.

That is, if the total spectral energy at the harmonic frequencies predicted from an engine is higher than other engines, it is reasonable to recognize it as target engine. To extract the spectral components at specific harmonic frequencies from JEM spectrum, frequency mask function is used. It is constructed from the blade number information and the spool rate.

Figure 4 shows the entire block diagram of the proposed JEM classification system. The spool rate is estimated from an input JEM time signal using autocorrelation or cepstrum method [13]. The spool rate estimated from this procedure can have a certain amount of error compared to the actual one. This error can cause serious problem in calculating harmonic frequencies and it can result in performance degradation. Therefore, in this paper we propose an algorithm to precisely estimate the spool rate and its detail algorithm will be described in the following section. The process of frequency mask generation is to create the frequency mask that passes the component of chopping frequencies and their harmonics and blocks the rest of frequencies in JEM spectrum. It is constructed from the estimated fine spool rate and the blade number information of each rotor stage from DB. That is, the frequency mask is generated as follows:

$$freqMask(eng, f) = \begin{cases} 1, & \text{if } f = m \cdot f_{1st}(eng, stg), \quad m = \pm 1, \pm 2, \ldots, \; stg = 1, 2, \ldots \\ 0, & \text{else} \end{cases} \tag{2}$$

where, $f_{1st}(eng, stg)$ denotes the first harmonic frequency, i.e., chopping frequency, at a rotor stage, *stg*, of an engine, *eng*. The chopping frequencies are calculated from Equation (1) using the blade number information and the estimated spool rate. The frequency masks are generated for all engines in the DB. The number of stages and harmonics used in the frequency mask can be limited considering the characteristic of radar waveform and engine. The JEM spectrum is obtained from the Fourier transform of input signal and is used to perform frequency masking. The process of frequency masking is to multiply the frequency mask and the JEM spectrum and add them as shown in Equation (3). It functions to extract all the spectral components at the frequencies with weight 1 in the frequency mask. The result of frequency masking is the masking score as follow:

$$maskingScore(eng) = \sum_f freqMask(eng, f) \cdot spectrum(f) \tag{3}$$

Finally, the engine with highest masking scores is classified as the target engine for the input JEM signal.

3.2. Fine Spool Rate Estimation

The fine spool rate estimation is to estimate the precise spool rate in frequency domain based on the spool rate estimated from the previous block. First, the spectral line with the largest amplitude except body Doppler in the spectrum is selected and let's denote it by f_0. This frequency has the highest possibility to be the first chopping frequency of the first rotor stage but it also can be its multiple. Whichever it is, the important thing is that the frequency is the multiple of the spool rate so the remainder when f_0 is divided by the spool rate, should be an integer. Of course, the spool rate estimated in the previous block has some estimation error so it may not be an integer exactly. To get an integer value, it is rounded off as follows:

$$N_0 = round\left(\frac{f_0}{spoolrate}\right) \tag{4}$$

If the estimation error exceeds the maximum round-off error, 0.5, the estimated integer, N_0, is not true. The problem is that we cannot guarantee that the integer N_0 is correct or not. Therefore we need a method to determine if the integer is true or not and to find the true value. In this paper, we propose a method that find a precise spool rate by comparing the frequency distance error between the multiple frequencies of a candidate spool rate and the real harmonic frequencies in JEM spectrum. As shown in Figure 5, we first set the frequency points that correspond to the multiples of a candidate spool rate (red solid line in the figure) and then all of the spectral components (blue line in the figure) in the JEM spectrum are assigned to the closest frequency points. Then the frequency distance between each frequency point and the spectral components assigned to it are calculated. If the candidate spool rate is exactly same to the actual one, the frequency distance error will be the smallest value. In contrast, as the candidate spool rate is far from the real one, the error will increases. By searching the neighbor of the spool rate estimated from the previous block, we can find the precise spool rate. Since the mathematical relationship between the spool rate and f_0 is an integer, we can reduce computation load by searching only for the candidate spool rates with integer relation. That is, the candidate spool rates can be restricted to several points around N_0 as given in Equation (5). For instance, if M set to 2, only 5 candidates are selected.

$$spoolrate_{candidate}(N) = \frac{f_0}{N}, \quad N_0 - M \le N \le N_0 + M \tag{5}$$

If all the spectral components are used when calculating the frequency distance error, computational load will increase remarkably. Furthermore, small spectral components around the harmonics rather work as noise. Therefore, by using only the harmonic peaks for calculating the frequency distance error as shown in Figure 5, we can get better performance in computation load and accuracy. The harmonic peaks that correspond to the multiple frequencies of the spool rate can be selected as follows:

$$\begin{gathered} f_{peak}^{N}(m) = \arg\max_{f}(S(f)), \\ (m-0.5) \times spoolrate_{candidate}(N) \le f, \quad (m+0.5) \times spoolrate_{candidate}(N) \ge f, \quad m = 1, \ldots, N \end{gathered} \tag{6}$$

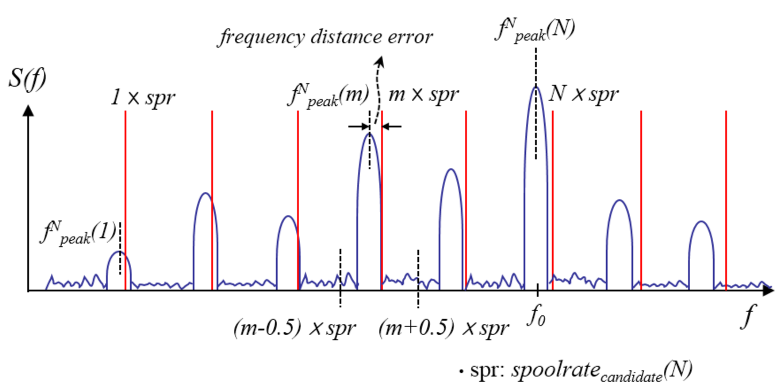

Figure 5. Concept of the frequency distance error between the multiples of a spool rate (red solid) and harmonics (blue) in JEM spectrum.

Then the sum of all frequency distance errors between the harmonic peak frequencies and the multiples of spool rate are calculated like Equation (7).

$$freqDistError(N) = \sum_{m=1}^{N} \left| f_{peak}^{N}(m) - m \times spoolrate_{candidate}(N) \right| \tag{7}$$

Finally, the precise spool rate is calculated as follows:

$$spoorate = \frac{f_0}{\arg\min\limits_{N}(freqDistError(N))} \tag{8}$$

4. EXPERIMENTAL RESULTS

4.1. Example of Target Classification

In this section, we will present the simulation result at each block of our proposed system for a given JEM signal. Figure 6 shows the spectrum of an input JEM signal. The largest spectral line is 45.62 Hz and it corresponds to the chopping frequency of an engine with 42 blades on the first rotor stage. The actual spool rate is 1.086 Hz but the spool rate estimated at the first block is 1.069 Hz, which has 1.57% of estimation error. By rounding off 42.68 (= 45.62/1.069), the estimated number of blades (or its multiple) is 43. Although the actual number of blades is 42, the integer is incorrectly estimated due to the error of the spool rate. We can get better result by using the proposed algorithm for fine spool rate estimation. The candidate spool rates within the range of ±2 around 43 are selected according to Equation (5) and Figure 8 shows the frequency distance errors calculated by Equation (7) for every candidates. In Figure 7, N_0 means the previously calculated integer, 43. Since the error is smallest at $N_0 - 1$, 42, we determine that the integer, 42, is the number of blades or its multiple. Where, the newly estimated spool rate is 1.0862 Hz and it is closer to the actual spool rate, 1.086 Hz.

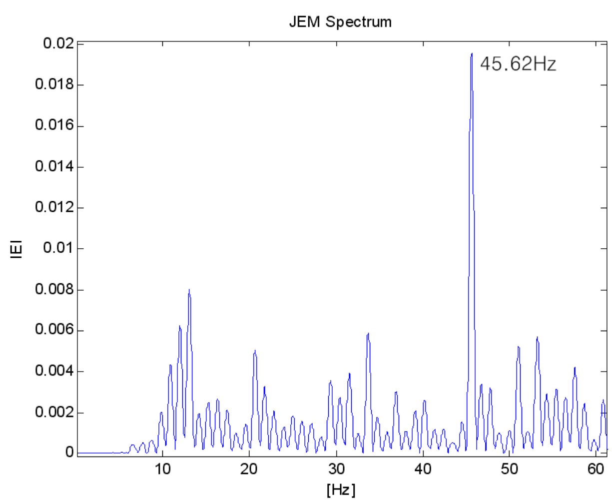

Figure 6. The spectrum of input JEM signal.

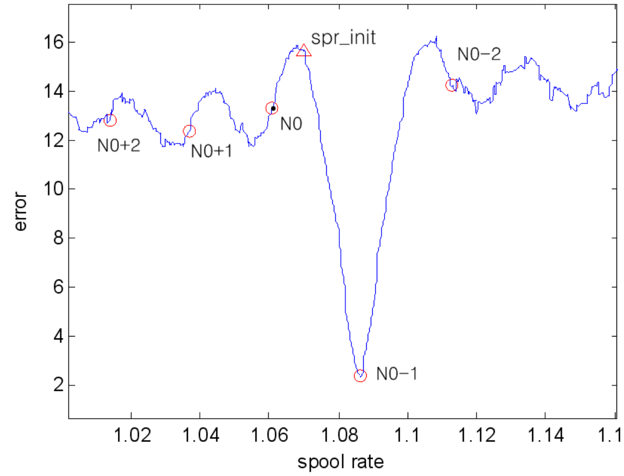

Figure 7. Frequency distance error with respect to spool rate.

Figure 8 shows the example of the frequency mask that is constructed from the estimated spool rate and the number of blades. It consists of the first to third harmonics for the first and second rotor stages. Their weights are all 1. Figure 9 shows the masking scores that are obtained from masking the JEM spectrum with the frequency masks for six engines in DB. The JEM spectrum in Figure 6 is for engine #1 and we can see that its masking score is highest in Figure 9. Finally engine #1 is classified as target engine.

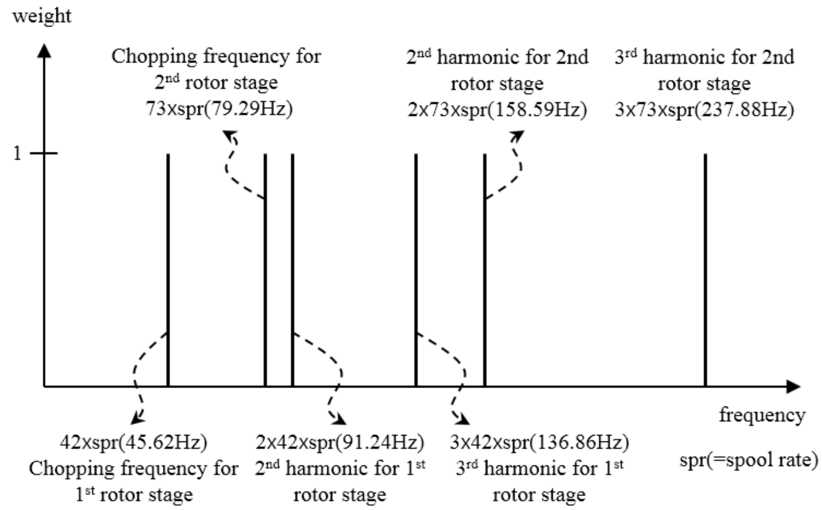

Figure 8. Frequency mask (Blade number of 42 on 1st stage and 73 on 2nd stage).

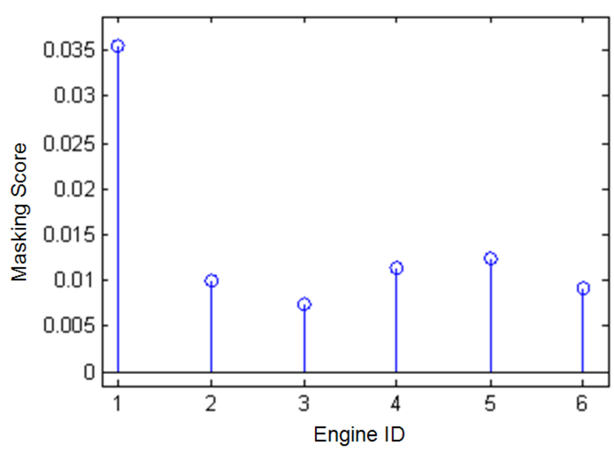

Figure 9. Masking scores for six jet engines.

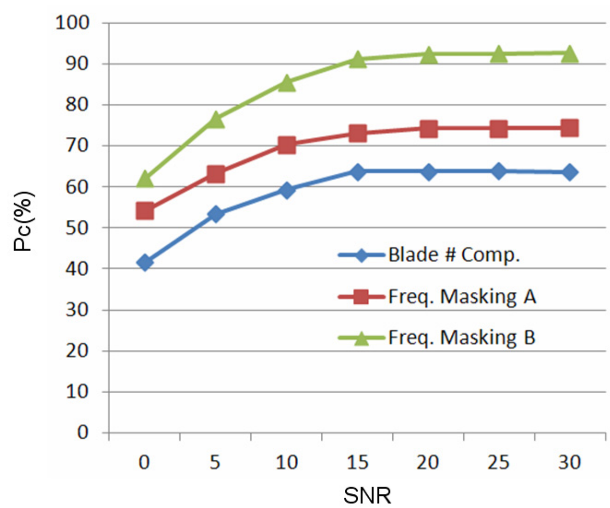

Figure 10. Comparison of classification rate with respect to SNR.

4.2. Classification Experiments Using Measured Signals

To verify the performance of the proposed system for a variety of data, we carried out classification experiments using the JEM signals that were measured from two realistic jet engine models [14]. The fabricated engine models have three rotor stages and the blades in each stage are attached to the rotating shaft at a 35 degree slantwise. The shaft is connected to a motor and its rotating speed is controlled. The number of blades in type A engine model are 42, 73, and 97 and ones in type B are 17, 29, and 41. Although RPM (Revolutions Per Minute) was limited to 180 Hz to reduce the transformation of blade shape when rotating, the characteristic of the measured spectrum is similar to the case with real (high) rotation speed because the relation between JEM spectrum and rotation speed is linear. The JEM signal used in the experiments has a variety of aspect angles and frequencies and they are shown in Table 1. The total number of JEM signals used in the test is 296 (165 for type A and 131 for type B). The length of JEM signal for Fourier analysis is 3 seconds and the frequency resolution is about 0.33 Hz.

Table 1. Information of the measured JEM data.

DB	Freq. (Hz)	Pol.	Aspect angle (degree)	RPM	PRF (Hz)
A_10_15G	10G, 5G	HH	$0 \sim 60$	60, 140, 180	900, 1800, 3600
A_08_16G	8G $\sim$ 16G	HH	$0 \sim 60$	60	1800
B_10_15G	10G, 15G	HH	$0 \sim 60$	60, 180	450, 900, 1800
B_08_16G	8G $\sim$ 16G	HH	$0 \sim 60$	60	1800

Six engine models including the type A and B, are used in the engine blade DB and their first and second stage blades are used for generating frequency mask. To compare the classification algorithms, we conducted the experiments for the following three cases.

(1) 'Blade number comparison' is the method to classify a target by estimating and comparing the number of blades in JEM spectrum.

(2) 'Frequency masking A' is the method to use the proposed frequency masking scheme but not to use the fine spool rate estimation.

(3) 'Frequency masking B' is the method to use the proposed frequency masking scheme with the fine spool rate estimation.

Table 2 shows the experimental result for the target classification using the JEM data and the algorithms mentioned above. The proposed frequency masking B shows better performance than the blade number comparison. In the case of frequency masking A method, its performance drops seriously in data A_10_15G. It is probably because type A has a large number of blades compared with type B, so the estimation error of spool rate affects the accuracy more seriously when calculating the harmonic frequencies in frequency mask, in particular high frequency. That is, from Equation (1) we can infer that the error in calculating the chopping frequency and its harmonics increases in proportion to the number of blades for a given spool rate. Applying the fine spool rate estimation in frequency masking B, we can see that its performance increases remarkably although type B's decreases a little bit.

Table 2. Comparison of classification rate [%].

DB	Blade number comparison	Frequency masking A	Frequency masking B
A_10_15G	77.7	29.9	85.3
A_08_16G	77.0	68.2	89.1
B_10_15G	58.6	98.2	96.0
B_08_16G	49.7	99.7	96.1
Average	65.8	74.0	91.6

Figure 10 shows the classification rate with respect to SNR. We can see that the proposed frequency masking method shows the excellent performance in noise environment and the fine spool rate estimation plays an important role for improving performance in the proposed scheme. The blade number comparison method used in the experiment was implemented based on [2], which does not present the specific algorithm to find the chopping frequency. We don't think that our implementation for the algorithm to find the chopping frequency is completely optimized so the performance could possibly be improved by enhancing the algorithm. Therefore, through the experimental results we don't hastily declare that the proposed method is superior to the blade number comparison method. But we can confirm that the proposed method can efficiently classify a jet aircraft without developing the complicated algorithm for estimating the number of blades itself.

5. CONCLUSION

In this paper, we propose a method to classify an aircraft with jet engine using the frequency masking of JEM spectrum. We confirm that the engine classification can be possible by comparing masking scores obtained from the masking process between JEM spectrum and the frequency mask generated from the number of blades and estimated spool rate. The proposed method shows better performance than the blade number comparison method in the classification experiment using the JEM signals measured from two fabricated engine models. In addition, by introducing the novel algorithm to estimate the precise spool rate in JEM spectrum, we can reduce the error in estimating the position of harmonic in frequency mask. In the future, the further study on the effect of different weights and the harmonics by inter-modulation in frequency mask will be conducted.

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