Higher Order Frequency Coupling Feature Extraction Using Three and One Half Dimension Spectrum Method

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Abstract

The conception of three and a half dimension spectrum is firstly defined, its own properties are analyzed in theory and simulation tests. Three and a half dimension spectrum can entirely suppress symmetrical distributed noise and frequency independent components. Employing three and a half dimension spectrum, which can be obtained via different definitions of fifth-order cumulant of complex signals, can extract the attended quartic or quadratic-to-cubic frequency coupling components or procreant frequency components for coupling, respectively. The original frequency components and procreant frequency components for coupling can also be synchronously extracted using three and a half dimension spectrum of real signals. The performance of three and a half dimension spectrum of complex signals or real signals is examined via simulation with underwater moving target-radiated data.
Keyword: Three and a half dimension spectrum, Fifth-order cumulant, Quadratic-to-cubic frequency coupling components

I. Introduction

One of important features of underwater acoustic channel is nonlinearity, when harmonic signals radiated by Underwater Moving Target(UMT) propagate in this channel, its output signal is likely to include original frequency components and procreant frequency components, which may include pairing frequency coupling components, quadratic frequency coupling components, and cubic frequency coupling components as well as other formal frequency components, duo to nonlinear coupling[1][2]. Extracting these frequency features can efficiently recognize the nonlinearity of systems and some features of the UMT. It is resultful to employ higher-order statistics for extracting these features. However, recently, frequency components of lower than cubic or pairing coupling can be separated using statistics of greater than two but lower than four. It is reported that quadratic frequency coupling feature was extracted using one and a half dimension spectrum or bispectrum[3],[4],[5] and cubic or pairing frequency coupling features were drawn out from all frequency components using two and a half dimension spectrum or trispectrum[1],[6]. Yet, it is not reported that frequency components of greater than cubic or pairing coupling are extracted via employing higher-order statistics or other methods in the given literatures.

In this paper, the feature and property of fifth-order cumulant spectrum are studied and analyzed in theory and simulation tests in order to explore the method for extracting higher order frequency coupling features of the UMT-radiated noise.

The organization of this paper is as follows. In section 2, we gave the definition of fifth order cumulant spectrum and studied its own features. Section 3 presented the estimation method of fifth order cumulant spectrum and showed the feature extraction results. Finally, some conclusions are obtained in section 4.

II. Definition and Property of Three and One Half Dimension Spectrum

Assume that the signal $x(k)$ at discrete time k is a zero-mean stationary real random process, then its fifth-order cumulants can be written as[7]

$$\begin{aligned} C_{5x}(\tau_1,\tau_2,\tau_3,\tau_4) &= cum\{x(k), x(k+\tau_1), x(k+\tau_2), x(k+\tau_3), x(k+\tau_4)\} \\ &= E[x(k)x(k+\tau_1)x(k+\tau_2)x(k+\tau_3)x(k+\tau_4)] - E[x(k)x(k+\tau_1)]E[x(k+\tau_2)x(k+\tau_3)x(k+\tau_4)] \\ &\quad - E[x(k)x(k+\tau_2)]E[x(k+\tau_1)x(k+\tau_3)x(k+\tau_4)] - E[x(k)x(k+\tau_3)]E[x(k+\tau_1)x(k+\tau_2)x(k+\tau_4)] \\ &\quad - E[x(k)x(k+\tau_4)]E[x(k+\tau_1)x(k+\tau_2)x(k+\tau_3)] - E[x(k+\tau_1)x(k+\tau_2)]E[x(k)x(k+\tau_3)x(k+\tau_4)] \\ &\quad - E[x(k+\tau_1)x(k+\tau_3)]E[x(k)x(k+\tau_2)x(k+\tau_4)] - E[x(k+\tau_1)x(k+\tau_4)]E[x(k)x(k+\tau_2)x(k+\tau_3)] \\ &\quad - E[x(k+\tau_2)x(k+\tau_3)]E[x(k)x(k+\tau_1)x(k+\tau_4)] - E[x(k+\tau_2)x(k+\tau_4)]E[x(k)x(k+\tau_1)x(k+\tau_3)] \\ &\quad - E[x(k+\tau_3)x(k+\tau_4)]E[x(k)x(k+\tau_1)x(k+\tau_2)] \end{aligned} \quad (1)$$

If in (1) time-delay $\tau_1 = \tau_2 = \tau_3 = \tau_4 = \tau$, fifth-order cumulant diagonal slice $C_{5x}(\tau,\tau,\tau,\tau)$ of random signal $x(k)$ can be given by following equation

$$\begin{aligned} C_{5x}(\tau,\tau,\tau,\tau) &= E\{x(k)x^4(k+\tau)\} - 4E\{x(k)x(k+\tau)\} \\ &\quad \cdot E\{x(k)x^2(k+\tau)\} - 6E\{x^2(k+\tau)\} \cdot E\{x(k)x^2(k+\tau)\} \end{aligned} \quad (2)$$

For convenience, let the fifth-order cumulant diagonal slice $C_{5x}(\tau,\tau,\tau,\tau)$ be written as $C_{5x}(\tau)$. Three and a half dimension spectrum of signal $x(k)$ is firstly defined by us and by following relation

$$CS_{5x}(f) \triangleq \int_{-\infty}^{\infty} C_{5x}(\tau) e^{-2\pi f \tau} d\tau \quad (3)$$

We regard (3) as three and a half dimension spectrum. Three and a half dimension spectrum is one of all higher order spectra and has ability to suppress Gaussian noise. However, It has its own properties and these properties are given as follows.

Property 1: If $n(t)$ at instantaneous time t satisfies the following conditions: (1) $n(t)$ is zero-mean, non-Gaussian random noise, (2) $n(t_1)$ and $n(t_2)$ for arbitrary $t_1 \neq t_2$ are irrelevant, (3) $p(n) = p(-n)$ for probability density function $p(n)$ of $n(t)$, then three and a half dimension spectrum of $n(t)$ is equal to zero, i.e.,

$$CS_{5n}(f) = 0$$

(4)

Proof: For noise $n(t)$, using (2), we have

$$\begin{aligned} C_{5n}(\tau) &= E\{n(t)n^4(t+\tau)\} - 4E\{n(t)n(t+\tau)\}E\{n(t)n^2(t+\tau)\} - 6E\{n^2(t+\tau)\}E\{n(k)n^2(t+\tau)\} \\ &= \delta(\tau)E\{n^5(t)\} - 10\delta^2(\tau) \cdot E\{n^2(t)\}E\{n^3(t)\} \end{aligned}$$

(5)

where $\delta(\tau) = \begin{cases} 1 & \tau = 0 \\ 0 & \tau \neq 0 \end{cases}$

According to the definition of mean value, we have

$$E[n^2(t)] = \int_{-\infty}^{\infty} p(n(t))n^2(t)dn(t)$$

(6a)

$$E[n^3(t)] = \int_{-\infty}^{\infty} p(n(t))n^3(t)dn(t)$$

(6b)

$$E[n^5(t)] = \int_{-\infty}^{\infty} p(n(t))n^5(t)dn(t)$$

(6c)

In (6), $p(n(t))$ and $n^2(t)$ are even function, $n^3(t)$ and $n^5(t)$ are odd function, so $E[n^2(t)] \neq 0$, $E[n^3(t)] = 0$, $E[n^5(t)] = 0$. Therefore, using (5) and (6), we have

$$C_{5n}(\tau) = 0$$

and

$$CS_{5n}(f) = \int_{-\infty}^{\infty} C_{5n}(\tau)e^{-j2\pi f\tau}d\tau = 0 \qquad (7)$$

Note that this property shows that three and a half dimension spectrum can entirely suppress symmetrical distributed noise. Namely, it is impossible to employ three and a half dimension spectrum to handle asymmetrical distributed noise.

Property 2: Assume that signal $x(k)$ is modeled as a sum of P sinusoids, i.e.,

$$x(k) = \sum_{i=1}^{P} A_i \cos(2\pi f_i k / f_s + \varphi_i)$$

where the amplitudes A_i's and phases φ_i's, f_i's are unknown constants. $i = 1, 2, \cdots, P$ and P is unknown. f_i's are independent each other, f_s is sampling frequency, then three and a half dimension spectrum of signal $x(k)$ is zero, i.e.,

$$CS_{5x}(f) = \int_{-\infty}^{\infty} C_{5x}(\tau)e^{-j2\pi f\tau}d\tau = 0$$

Proof of property 2 is given by the reference[2].

Definition: Assume that the signal $x(k)$ is a zero-mean stationary complex random process, then definition of its fifth-order cumulant has thirty-two different forms obtained by taking the conjugate to different terms among $x(k)$, $x(k+\tau_i)(i = 1`, 2, 3, 4)$. Two of thirty-two different definitions are given by

$$C_{5x}(\tau_1, \tau_2, \tau_3, \tau_4) = \text{cum}\{x^*(k), x(k+\tau_1),\ x(k+\tau_2), x(k+\tau_3), x(k+\tau_4)\}$$

(8)

$$C_{5x}(\tau_1, \tau_2, \tau_3, \tau_4) = \text{cum}\{x^*(k), x^*(k+\tau_1),\ x(k+\tau_2), x(k+\tau_3), x(k+\tau_4)\}$$

(9)

Assume that $x(k)$ is a complex harmonic signal, i.e.,

$$x(k)=\sum_{b=1}^{P} A_b \exp[j(\omega_b k+\varphi_b)]$$

where the amplitudes A_b's ($b=1,2,3,\cdots$), the phases φ_b's, and the circle frequency ω_b's given by $2\pi f_b / f_s$ are constants.

Property 3: If in (10) $x(k)$ is a quartic frequency coupling complex signal[7], its three and a half dimension spectrum is given by

$$CS_{5x}(f)=\sum_{i=1}^{P}\sum_{l=1}^{P}\sum_{m=1}^{P}\sum_{n=1}^{P}\sum_{r=1}^{P} A_i A_l A_m \cdot A_n A_r \delta(f_l+f_m+f_n+f_r-f) \quad (10)$$

Proof: For the quartic frequency coupling complex harmonic signal $x(k)$ in (10), we have

$$\begin{cases} f_i = f_l + f_m + f_n + f_r \\ \varphi_i = \varphi_l + \varphi_m + \varphi_n + \varphi_r \end{cases} \; (i,l,m,n,r=1,2,\cdots,P) \quad (12)$$

Substituting (10) into (8) and using (11), the fifth-order cumulant of the signal $x(k)$ is given by

$$C_{5x}(\tau_1,\tau_2,\tau_3,\tau_4)=\sum_{i=1}^{P}\sum_{l=1}^{P}\sum_{m=1}^{P}\sum_{n=1}^{P}\sum_{r=1}^{P} A_i A_l A_m \; A_n A_r \exp\{j[2\pi(f_l\tau_1+f_m\tau_2+f_n\tau_3+f_r\tau_4)/f_s]\} \quad (13)$$

Specifically, set $\tau_1=\tau_2=\tau_3=\tau_4=\tau$ in (13) to see that

$$C_{5x}(\tau)=\sum_{i=1}^{P}\sum_{l=1}^{P}\sum_{m=1}^{P}\sum_{n=1}^{P}\sum_{r=1}^{P} A_i A_l A_m A_n A_r \exp[j2\pi f_i \tau / f_s] \quad (14)$$

Therefore, we have

$$CS_{5x}(f)=\int_{-\infty}^{\infty}\left\{\sum_{i=1}^{P}\sum_{l=1}^{P}\sum_{m=1}^{P}\sum_{n=1}^{P}\sum_{r=1}^{P} A_i A_l A_m A_n A_r \cdot \exp[j2\pi f / f_s]\exp[-2\pi f \tau]\right\} d\tau$$

(15)

From (15), we can obtain (11). It is seen that three and a half dimension spectrum of complex harmonic signal $x(k)$ can draw out quartic frequency coupling component.
Property 4: If in (10) $x(k)$ presents quadratic-to-cubic frequency coupling complex signal[7], its three and a half dimension spectrum is expressed by

$$CS_{5x}(f)=-\sum_{b=1}^{P} A_b^5 \delta[2\pi(f_b-f)/f_s] + \sum_{i=1}^{P}\sum_{l=1}^{P}\sum_{m=1}^{P}\sum_{n=1}^{P}\sum_{r=1}^{P} A_i A_l A_m A_n A_r \cdot \delta[2\pi(-f_l+f_m+f_n+f_r-f)/f_s]$$

(1 6)

Proof: For $x(k)$ in (10), the case of quadratic- to-cubic frequency coupling, we have[7]

$$\begin{cases} f_i + f_l = f_m + f_n + f_r \\ \varphi_i + \varphi_l = \varphi_m + \varphi_n + \varphi_r \end{cases} \; (i,l,m,n,r=1,2,\cdots,P)$$

(17)

Based on (10), (9) and (16), the fifth-order cumulant of signal $x(k)$ can be obtained by

$$C_{5x}(\tau_1,\tau_2,\tau_3,\tau_4)=-\sum_{b=1}^{P} A_b^5 \exp[j2\pi f_b(-\tau_1+\tau_2+\tau_3+\tau_4)/f_s] + \sum_{i=1}^{P}\sum_{l=1}^{P}\sum_{m=1}^{P}\sum_{n=1}^{P}\sum_{r=1}^{P} A_i A_l A_m A_n A_r$$

$$\cdot \exp\{j[2\pi(-f_l\tau_1 + f_m\tau_2 + f_n\tau_3 + f_r\tau_4)/f_s]\} \quad (18)$$

when $\tau_1 = \tau_2 = \tau_3 = \tau_4 = \tau$ in (18), fifth- order cumulant diagonal slice $C_{5x}(\tau)$ of $x(k)$ can be calculated by

$$C_{5x}(\tau) = -\sum_{b=1}^{P} A_b^5 \exp[2\pi f_b \tau / f_s] + \sum_{i=1}^{P}\sum_{l=1}^{P}\sum_{m=1}^{P}\sum_{n=1}^{P}\sum_{r=1}^{P} A_i A_l A_m A_n A_r \cdot \exp\{j[2\pi(-f_i + f_l + f_m + f_n + f_r)\tau / f_s]\} \quad (19)$$

Fourier transform of (19) is equal to (16). It is obvious that three and a half dimension spectrum of complex signal $x(k)$ can extract quadratic-to-cubic frequency coupling components and quadratic frequency components.

III. Three and One Half Dimension Spectrum Estimation and Tests

Three and a half dimension spectrum of random signal $x(k)$ is estimated by the following steps.

Step 1: The measured data $\{x_1, x_2, \cdots, x_L\}$ are divided into K groups, each group has M point data, and $L = KM$, as well as L, K and M are integer. Each data minus the mean-value of this group data.

Step 2: Assume that $\{x^{(i)}(k)$, k=1, 2, ⋯, M-1$\}$ is the data of the ith group, and $i = 1, 2, \cdots, P$. Three and a half dimension spectrum of each group data is estimated by the following formulation

$$C_{5x}^{(i)}(\tau) = \frac{1}{M}\sum_{k=M_1}^{M_2} x^{*(i)}(k)[x^{(i)}(k+\tau)]^4 - 4\frac{1}{M}\sum_{k=M_1}^{M_2} x^{*(i)}(k)x^{(i)}(k+\tau) \cdot \frac{1}{M}\sum_{k=M_1}^{M_2}[x^{*(i)}(k+\tau)]^3 - 6\frac{1}{M}\sum_{k=M_1}^{M_2}[x^{*(i)}(k+\tau)]^2 \cdot \frac{1}{M}\sum_{k=M_1}^{M_2} x^{*(i)}(k)[x^{(i)}(k+\tau)]^2 \quad (20)$$

or

$$C_{5x}^{(i)}(\tau) = \frac{1}{M}\sum_{k=M_1}^{M_2} x^{*(i)}(k)x^{*(i)}(k+\tau)[x^{(i)}(k+\tau)]^3 - 4\frac{1}{M}\sum_{k=M_1}^{M_2} x^{*(i)}(k)x^{*(i)}(k+\tau) \cdot \frac{1}{M}\sum_{k=M_1}^{M_2}[x(k+\tau)]^3 - 6\frac{1}{M}\sum_{k=M_1}^{M_2} x^{*(i)}(k)x^{(i)}(k+\tau) \cdot \frac{1}{M}\sum_{k=M_1}^{M_2} x^{*(i)}(k)[x^{(i)}(k+\tau)]^2 - 3\frac{1}{M}\sum_{k=M_1}^{M_2}[x^{(i)}(k+\tau)]^2 \cdot \frac{1}{M}\sum_{k=M_1}^{M_2} x^{*(i)}(k)x^{*(i)}(k+\tau)x^{(i)}(k+\tau) \quad (21)$$

or

$$C_{5x}^{(i)}(\tau) = \frac{1}{M}\sum_{k=M_1}^{M_2} x^{(i)}(k)[x^{(i)}(k+\tau)]^4 - 4\frac{1}{M}\sum_{k=M_1}^{M_2} x^{(i)}(k)x^{(i)}(k+\tau) \cdot \frac{1}{M}\sum_{k=M_1}^{M_2} x^{(i)}(k)[x^{(i)}(k+\tau)]^2$$

$$-6\frac{1}{M}\sum_{k=M_1}^{M_2}[x^{(i)}(k+\tau)]^2\cdot\frac{1}{M}\sum_{k=M_1}^{M_2}x^{(i)}(k)[x^{(i)}(k+\tau)]^2 \quad (22)$$

where $M_1=\max(0,-\tau)$, $M_2=\min(M\text{-}1,M\text{-}1\text{-}\tau)$.

Step 3: Mean value of $C_{5x}^{(i)}(\tau)$ of all groups is regarded as the fifth order cumulant diagonal slice estimation of all measured data, i.e.,

$$\hat{C}_{5x}(\tau)=\frac{1}{K}\sum_{i=1}^{K}C_{5x}^{(i)}(\tau) \quad (23)$$

Step 4: We turn $\hat{C}_{5x}(\tau)$ at time domain τ into $CS_{5x}(f)$ at frequency domain f via Fourier transform for (23), i.e.,

$$CS_{5x}(f)=\frac{1}{N}\sum_{\tau=0}^{N-1}\hat{C}_{5x}(\tau)\exp(-j2\pi f\tau)=\frac{1}{K}\sum_{i=1}^{K}CS_{5x}^{(i)}(f) \quad (24)$$

where $CS_{5x}^{(i)}(f)=\frac{1}{N}\sum_{\tau=0}^{N-1}C_{5x}^{(i)}(\tau)\exp(-j2\pi f\tau)$

Step 5: Normalized three and a half dimension spectrum $NCS_{5x}(f)$ is defined by

$$NCS_{5x}(f)=10\log_{10}\left|\frac{CS_{5x}(f)}{max\{CS_{5x}(f)\}}\right|(\mathrm{dB}) \quad (25)$$

From above analysis, it is obvious that we can obtain more phase information from three and a half dimension spectrum than power density spectrum of the measured data. In order to analyze the performance of three and a half dimension spectrum, feature extraction tests with Underwater Moving Target(UMT)- radiated data are carried out. In these tests, sampling frequency f_s, total data points L, each group length M, and maximum time-delay $\tau_{\max}$ are 15*k*Hz , 8192, 256 and 64, respectively. Table 1 and Table 2, Fig.1 and Fig.2 show the results of feature extraction tests.

Table 1. Extracted frequencies of quartic frequency coupling components (unit:Hz)

Groups	First	Second
Attended frequency coupling components	354.2845 (a)	633.2345 (A)
	453.6768 (b)	924.8765 (B)
	700.1234 (c)	1654.2354 (C)
	1401.4587 (d)	2789.2111 (D)
Procreant frequency component duo to coupling	2909.6346 (2)	6001.5566 (1)

Note: In the bracket ( ) of Table 1, sequence number a, b, c, d, 2 ,A, B, C, D, 1 is corresponding the sequence number in Fig.1.

Table 2. Extracted frequencies of quadratic-to-cubic frequency coupling components (unit:Hz)

Groups	First	Second
Attended frequency coupling component	133.9875 (a)	450.9760 (b)
	1924.4321 (e)	700.1223 (c)
		907.3213 (d)

Procreant frequency component for coupling	2058.4196 (1)	2058.4196 (1)

Note: In the bracket ( ) of Table 2, sequence number a, b, c, d, e, 1 correspond to the sequence number in Fig.2. Sum of frequencies of the first group is equal to sum of the second group.

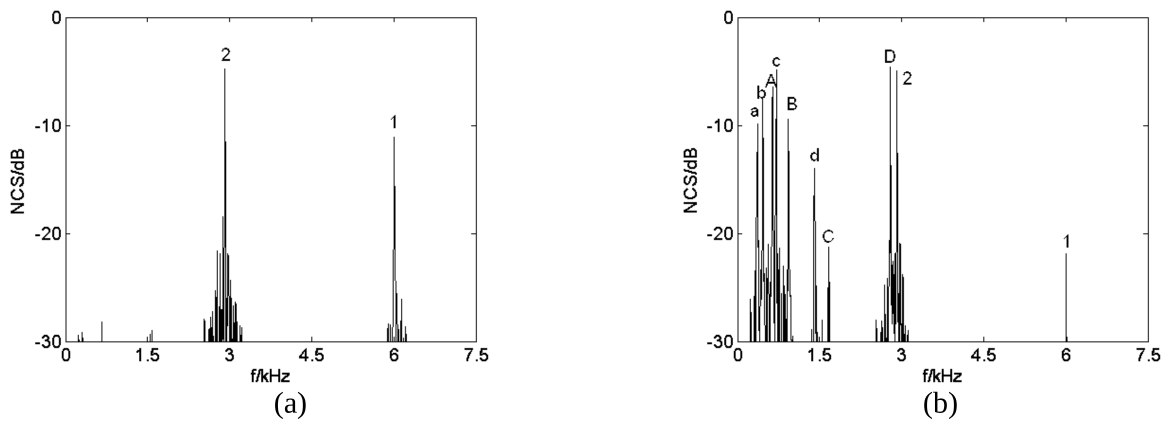

Fig.1. This shows normalized three and a half dimension spectrum(denoted by NCS) of quartic frequency coupling feature radiated by underwater moving target(UMT). Fig.1(a) shows the extracted result using (20) . Fig.1 (b) shows the extracted result using (22).

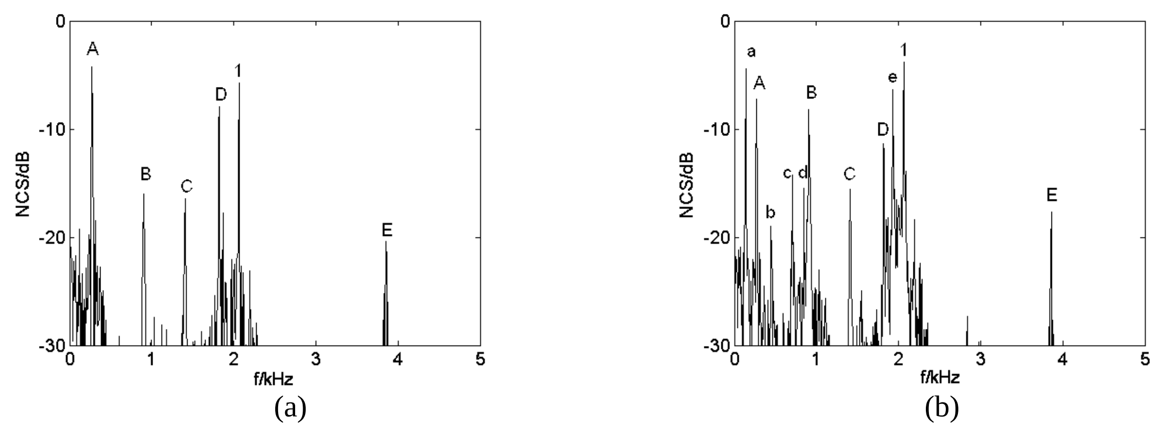

Fig.2. This shows normalized three and a half dimension spectrum(denoted by NCS) of quadratic-to-cubic frequency coupling feature radiated by the UMT. Fig.2(a) shows the extracted result using (21) . Fig.2 (b) shows the extracted result using (22).

In Fig.1(a), spectrum peaks *1* and *2* are novel procreant frequency components duo to quartic frequency coupling. Their frequencies were extracted using three and a half dimension spectrum of complex signals. In Fig.1(b), spectrum peaks *a, b, c, d, A, B, C*, and *D* are attended quartic frequency coupling components. Fig.1 and Table 1 have shown the extracted results using three and a half dimension spectrum. In Fig.2, a spectrum peak *1*, which is brought via quadratic-to-cubic frequency coupling, is a novel frequency component. In Fig.2(b), spectrum peaks *A, B, C, D*, and *E* are novel procreant double frequency components for quadratic-to-cubic frequency coupling. Peaks *a, b, c, d*, and *e* are attended quadratic-to-cubic frequency coupling components. Fig.2 and Table 2 have shown the extracted results using three and a half dimension spectrum.

IV. Conclusions

Higher order frequency coupling feature is one of important features of complex nonlinear vibration system. It is very necessary and valid to employ higher order spectrum for analyzing these nonlinear features. According to our research results, we can come to following conclusions:

(1) Three and a half dimension spectrum is a new conception and has its own properties and function, which are different from one and a half dimension spectrum and two and a half dimension spectrum.

(2) Three and a half dimension spectrum, which can be obtained via different definitions of the fifth-order cumulant of complex signals, can extract original frequency components or procreant frequency components for coupling.

(3) Attended quartic or quadratic-to-cubic frequency coupling components, procreant frequency components for coupling can also be efficiently extracted using three and a half dimension spectrum of complex signals.

(4) Three and a half dimension spectrum of real signals can synchronously extract attended quartic or quadratic-to-cubic frequency coupling components and procreant frequency components for coupling.

(5) Three and a half dimension spectrum of complex signals or real signals can entirely suppress independent frequency components.

From above conclusions, we can know that method of three and a half dimension spectrum is flexible and convenient under condition of existing higher order coupling. This researchful ideology provides a direction for extracting much higher order frequency coupling feature using higher order spectrum.

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