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Research Article

The Smoothed Pseudo Wigner Ville Distribution for the Ship Shafting Torsional Vibration Signals Analysis

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Keywords

Improved Smoothed Pseudo Wigner Ville Distribution (ISPWVD), Ship Shafting, Torsional Vibration Signal.

Abstract

The paper shows the ship shafting torsional vibration signal analysis using the Improved Smoothed Pseudo Wigner Ville Distribution (ISPWVD). The torsional vibration frequency components are complex and signals are variable frequency signals (or more precisely: linear frequency modulated signals, i.e. the whole shafting is constant acceleration or deceleration). The processing method of the torsional vibration signals is introduced in the study. In this paper, it is confirmed that the signal processing method of the torsional vibration is feasible through the actual experiment and has practical significance for the ship shafting torsional vibration analysis.

1. Introduction

Vibratory forces generated in ship propulsion systems by main engine, shaft, propeller and gearbox as well as by wave, current and imbalanced ship loads are often unavoidable. These forces have influence on axial, radial and torsional vibrations. When the oscillation motion is twisting the rotor, the torsional vibration will be generated. Unchecked torsional vibration can cause cracking, crankshaft failure, failure of the parts or excessive wear and tear of bearings and gear parts. The paper shows the ship shafting torsional vibration signal analysis performance by using ISPWVD. The central idea is to obtain a signal's energy concentration distribution in time-frequency domain without aliasing or cross components, and so that closely spaced components can be easily distinguished.

2. The Improved Smoothed Pseudo Wigner Ville distribution (ISPWVD)

The Wigner distribution (WD) is perhaps the most prominent quadratic time-frequency (TF) representation. It was originally defined in a quantum mechanical context by Wigner in 1932. Ville introduced the WD in a signal analysis context in 1948[1]. The Wigner Ville distribution（WVD）is ideal for the linear frequency modulated (FM) signal, and exhibits many beneficial properties, including energy conservation, time and frequency shift invariants, or compatibility with filters; the details are described by Cohen [2].

The WVD of a real signal *s(t)* is expressed as Eq (1)

$$WVD_x(t,f)=\int_{-\infty}^{\infty}x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})e^{-j2\pi f\tau}d\tau \qquad (1)$$

where *x(t)* is the analytic signal associated with the real signal *s(t)*[3]. The analytic signal *x(t)* of a signal *s(t)* is defined as *x(t)=s(t)+iH[s(t)]*, where *H[s(t)]* is the Hilbert Transform of the signal *s(t)*; the Hilbert Transform is sometimes referred to as a "quadrature filter" and the transformed signal as the "quadrature signal".

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In order to compute WVD, the signal must be sampled. For the limited bandwidth signals (i.e. if $|\omega|>\omega_0$, $x(\omega)=0$), and the signal sampling interval is T ,WVD was given by Eq. (2).

$$WVD_x(nT,\omega)=2T\sum_{k=-\infty}^{\infty}x((n+k)T)x^*((n-k)T)\exp(-j2\omega kT) \tag{2}$$

The WVD has cross-term interference, which appears as frequencies that lie between the any two adjacent strong frequencies components. In general, the Pseudo Wigner Ville distribution (PWVD) and the Smoothed Pseudo Wigner Ville distribution (SPWVD) are often used for suppressing cross-term interference (Eq. (3)).

$$PWVD_x(t,f)=\int_{-\infty}^{\infty}\phi(\frac{\tau}{2})\phi^*(-\frac{\tau}{2})x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})e^{-j2\pi f\tau}d\tau \tag{3}$$

According to its Cohen's kernel function, the PWVD is concentered on the frequency axis. In the PWVD the time windowing acts as a frequency smoothing. Therefore, the PWVD suppresses the Wigner distribution interference components that oscillate in the frequency direction.

The discrete form of Eq. (3) is Eq. (4)

$$PWVD_x(t,f)=\int_{-\infty}^{\infty}\phi(\frac{\tau}{2})\phi^*(-\frac{\tau}{2})x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})e^{-j2\pi f\tau}d\tau \tag{4}$$

where $\omega=2\pi f$, $\phi(k)$ is a window function that the signal near the time being analyzed will have higher weight. The length of $\phi(k)$ is $2L-1$.

In the time direction, time smoothing can be implemented by a time-convolution of the Pseudo Wigner distribution (Eq. (5)).

$$SPWVD_x(t,f)=\int_{-\infty}^{\infty}q(t-u)\int_{-\infty}^{\infty}\phi(\frac{\tau}{2})\phi^*(-\frac{\tau}{2})x(u+\frac{\tau}{2})x^*(u-\frac{\tau}{2})e^{-j2\pi f\tau}d\tau du \tag{5}$$

where the operations *q* is a lowpass function.

The discrete form of Eq. (5) is Eq. (6):

$$SPWVD_x(n,\omega)=2\sum_{j=L_1+1}^{L_1-1}\sum_{k=L_2}^{L_2-1}q(n-j)\phi(k)\phi^*(-k)x(j+k)x^*(j-k)\exp(-j2k\omega) \tag{6}$$

where the length of $\phi(k)$ is $2L_2-1$, and $q(j)$ is $2L_1-1$.

The literature [3] shows that a correct use of the Wigner Distribution (WD) for time-frequency signal analysis requires use of the analytic signal. The method does not exhibit any aliasing problem, and introduces no frequency artifacts. The problems introduced by the use of the Wigner Distribution with a real signal are clarified. The Wigner distribution function is also equivalent to the rotation operation of the Gabor transform [4]. Compared with the WVD, the Gabor transform does not have the cross-term problem. This advantage is important for developing a new method for interference reduction. Soo-Chang Pei [5] uses the Gabor transform instead of the WVD to perform signal processing, and they combines the advantages of the Gabor transform (no cross term) and the WVD (high clarity) to find out the Gabor-Wigner transform. In a word, the optimal kernel distributions design is important, and they are based on the distribution norms, i.e. sums of the distribution values. When the cross terms appeared, the norms failed to behave in the desired way. A fast algorithm has been developed for solving the linear program, allowing the computation of the signal-dependent Time-frequency distributions with a time complexity on the same order as a fixed-kernel distribution [6]. A signal-dependent kernels that changes shape for each signal to offer improved time-frequency representation for a large class of signals by R.G. Baraniuk, D.L. Jones [7]. The literature [8] indicates that SPWVD provides a good resolution at high frequency and a good frequency resolution at low frequencies in dependently if signals remain stationary. The literature [9] provides a coherent framework for intuitive strategies aimed at detecting chirp like signals by some line integration in the time–frequency plane. It is common to convert a real signal into a analytic signal prior to the Wigner Ville transform by applying the Hilbert transform. It must be emphasized that various examples of application of such an approach have already been proposed in the literature, e.g., in [10, 11,12] or, more recently in [13, 14,15,16]. A new method for interference reduction in the Smoothed Pseudo Wigner-Ville distribution is described by Stanislav Pikula, Petr Beneš [15]. They believe that if nonlinear FM signals are included in the analyzed signal, these constitute an indivisible portion of the result, and the different time and frequency window widths in the SPWVD affect the resulting presence of the interferences and Time-Frequency (TF) resolution, then they focus on the growing window impact at different points in the TF plane. For a single TF point, the algorithm finds the minimal difference between two consecutive SPWVDs. Two SPWVDs with such minimal difference then constitute the ideal smoothing for a concrete TF point. The actual estimated value is calculated as the mean of the two values provided by the two SPWVDs for the concrete TF point. The described method is repeated for all TF points within the whole TF plane [15]. The disadvantage of the algorithm is the need of multiple calculations of the SPWVD. The literature [16] considers that the motor is operating in continuous non-stationary operating conditions, and the windowed Fourier ridges was used for the detection of rotor faults. The torsional vibration signal was analyzed in this paper using the new method that's put forward by Stanislav Pikula & Petr Beneš [15]. The other characteristics and data processing method of the torsional vibration signals also discussed in the paper.

3. Testing signals

To illustrate the application of the Improved Smoothed Pseudo Wigner-Ville distribution, several examples are shown below.

Example 1. The first testing signal chosen is with constant amplitude *(A=0.5md)*, and with a constant frequency *(f=15Hz)*, the signal *s(t)* is given as.

$$s(t)=0.5\times\sin(30\pi t-\frac{30\pi}{180}) \tag{7}$$

Considering data sampling frequency is at 80Hz, a signal of containing a 15Hz sinusoid with amplitude 0.5um and disturbing it with some zero-mean random noise was formed. Figure 1 is FFT spectrum of signal *s(t)*, the above picture in Figure 1 is single-sided amplitude spectrum of signal *s(t)*, a constant frequency component *(f=15Hz)* was represented, and the following picture in Figure 1 is a phase frequency spectrum of signal *s(t)*, it reveals that when the frequency is equal to 15Hz, the corresponding phase angle suddenly changes.

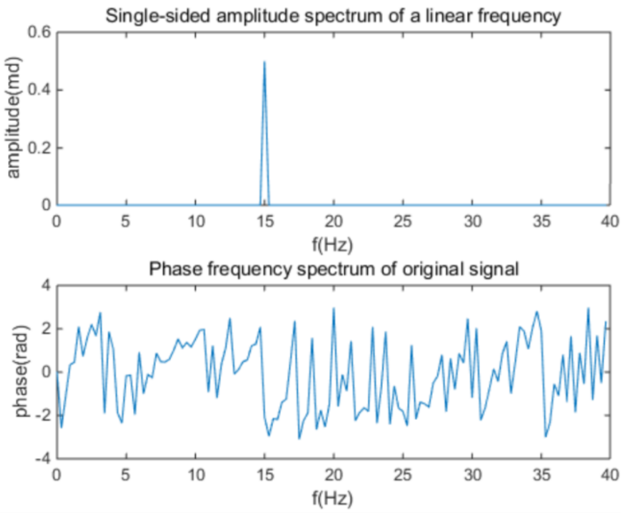

Figure 1. FFT spectrum of *s(t)*

Figure 2 shows that interference terms (or cross terms) present in a real signal can be avoided by computing the analytic signal. This illustrates that the analytic signal should be used for a better time-frequency analysis in using SPWVD.

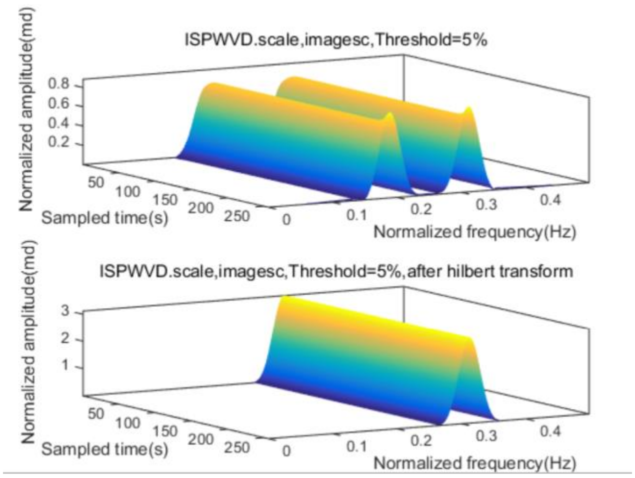

Figure 2. ISPWVD spectrum of *x(t)*

Using the analytic signal, the advantages are:

(1) The positive and negative frequency interference components near the zero frequency were eliminated.

(2) Because the analytical signal spectrum is a unilateral spectrum, so frequency folding phenomenon is not going to happen in Wigner Ville distribution.

(3) The sampling frequency can be selected according to the Nyquist frequency in Wigner Ville distribution, and interference terms were disappear. When the analytic signal is used as the input signal, the sampling rate criterion for the time signal is restored to the normal Nyquist sampling criterion, i.e., the signal must be sampled at a frequency at least twice as high as the highest frequency content in the signal [11].

If sampling frequency(f_s) was chosen appropriately, the calculation result of real value input signal is correct by using ISPWVD, but the ISPWVD function was expecting the analytic signal, the usage of real value input signal may be incorrect. What's the meaning of appropriate f_s ? Because the cycle of frequency variable in WVD is π ,the cycle of frequency variable discrete Fourier transform is 2π , i.e. if the real signal is as input signal, sampling frequency (f_s) should be 2 times the Nyquist frequency in WVD. In this case, interference terms present in a real signal input also can be avoided. It is important to note that the sampling rate should be at least four times of frequency of interest if aliasing is avoided [11].

Here, the paper shows that a correct use of the Wigner Ville distribution for a signal analysis. There was no difference between FFT and SPWVD, the method demonstrates that FFT and SPWVD can be used interchangeably in stationary signals [8].

Example 2. The second testing signal chosen, is with linear frequency modulation signal constant frequency signals, constant amplitude *(A=1md)*, and with seven constant frequencies *(f_i=5Hz…35Hz),* see Figure 3, the signal *s(t)* is given as

$$s(t) = fmlin(n,0,0.5,\frac{n}{2}) + \sum_{i=1}^{7}\sin(f_i t - \frac{30\pi}{180}) \quad (8)$$

where *fmlin* is a frequency modulation function, *n* is number of points, *0* is initial normalized frequency, *0.5* is final normalized frequency, time reference for the phase is $n/2$.

Figure 3 shows the FFT spectrum of the signal *s(t)*, which has a linear frequency modulation component and seven constant frequency components. The above picture in Figure 3 is that one linear frequency modulation with seven constant frequency spectrums were represented, and the following picture in Figure 3 is a phase spectrum. The phase difference between exciting and response is very low at the low frequency stage in this diagram, the exciting and response are basically synchronous, without too much delay. But it is different at the high frequency stage, the system is not to be able to reflect the difference due to inertia effect , therefore, it reveals that when the frequency respectively were equal to 20Hz,25Hz,30Hz,35Hz, the corresponding phase angle suddenly changes.

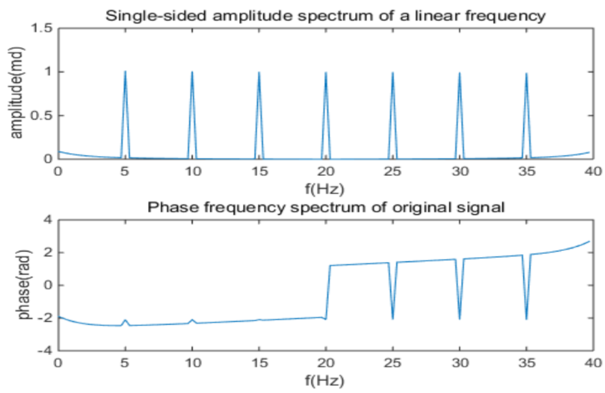

Figure 3. FFT spectrum of linear frequency modulation signal *s(t)*

Figure 4 is a profile of ISPWVD spectrum, it not only shows seven constant frequency components, but also shows one linear frequency modulation component.

However, when applied WVD to a signal with multi frequency components, interference terms appear because quadratic nature of WVD. But using the new method that's put forward by Stanislav Pikula & Petr Beneš [3], interference terms can be eliminated, and the signal components were correctly characterized.

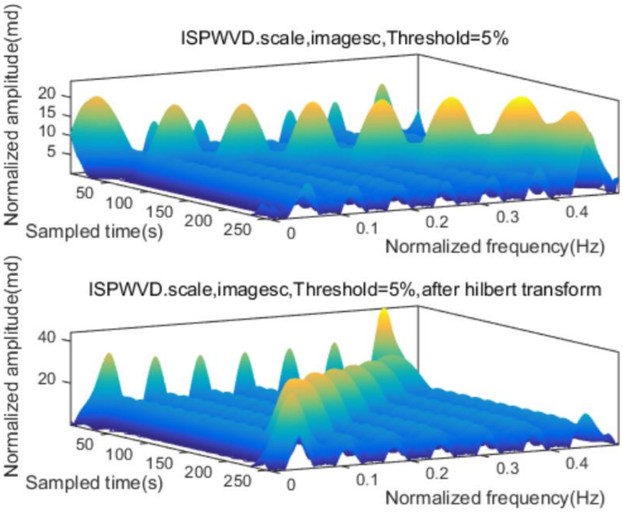

Figure 4. ISPWVD spectrum of linear frequency modulation

Figure 4 is a profile of ISPWVD spectrum, it not only shows seven constant frequency components, but also shows one linear frequency modulation component.

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4. Experiment

Experimental facilities:

The motor of an experimental four-pole (p=2) three phase induction machine is equivalent to that the rotor is mounted centrally between two bearings 90mm apart, the shaft diameter is 20mm, and a coupler is jointed with it, a disk with 60 teeth (i.e. rotor) is mounted between another two bearings 510mm apart. The disk position is at the location that is the 1/3 length of a shaft, which is 612 mm length and its diameter is 30 mm.

This is a three-disk (rotor, joint, disk) four-bearing rotor system.

Equipment model: Motor model: Y2-90s-4,Motor Power:1.1kw,Rated speed:1440r/m;precision aluminum alloy coupler, HTA Rotary encoder,Type:Z58/12K/6L-200P/R. Bearing:1505.

The qualitative analysis of torsional vibration signal:

The autocorrelation function and partial autocorrelation function of actual acquisition signal have been calculated.

Under normal circumstances, the convergence speed of autocorrelation function reflects that how many frequency components a signal have. The signal autocorrelation function of random component always tends to zero, or a certain value along with time. See Figure 6, the random signal is a normally distributed pseudorandom numbers, its autocorrelation function value tends to a certain value along with time.

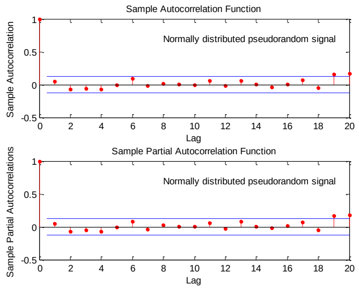

Figure 6. Random signal autocorrelation and partial autocorrelation function

Whereas the signal autocorrelation function of the periodic components is always keeping the original periodic property and not attenuating. See Figure 7, the periodic function is

$$s(t)=\sin(2\times\pi\times5\times t-30\times\frac{\pi}{180})+\sin(2\times\pi\times10\times t-30\times\frac{\pi}{180})+\sin(2\times\pi\times15\times t-30\times\frac{\pi}{180}) \quad (9)$$

The function curve is not decay

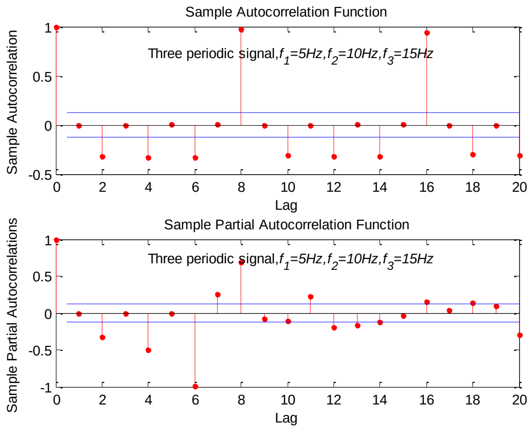

Figure 7. Three periodic signal autocorrelation and partial autocorrelation function

Based on the definition of autocorrelation function and partial autocorrelation function, the autocorrelation function and partial autocorrelation function properties of amplitude modulation signal and frequency modulation signal have been studied. For amplitude modulation signal, autocorrelation function can be fully characterized. See Figure 8, it is a superposition of two one-sided exponential amplitude modulation. It is represented obviously in sample autocorrelation function, but cannot be represented obviously in sampling partial autocorrelation function.

Whereas the frequency modulation signal, the part autocorrelation function can be fully characterized. See Figure 9, it is a superposition of two linear frequency modulation signal. It is represented obviously in sample partial autocorrelation function, but cannot be represented obviously in sampling autocorrelation function.

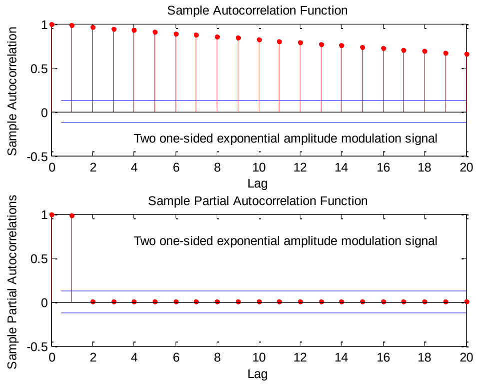

Figure 8. signal autocorrelation and partial autocorrelation function of amplitude modulation

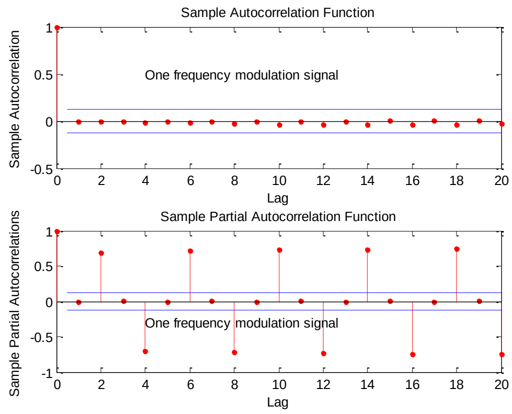

Figure 9. signal autocorrelation and partial autocorrelation function of linear frequency modulation

Figure 10 shows the curve of autocorrelation function and partial autocorrelation function of actual acquisition torsional vibration signal, which may be a periodic signal with frequency modulation.

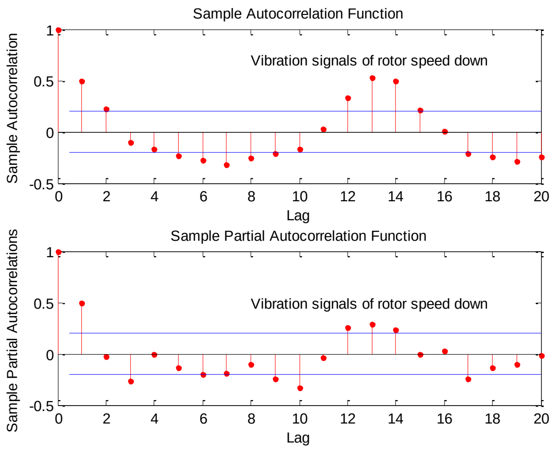

Figure 10. autocorrelation function and partial autocorrelation function of the actual acquisition torsional vibration signal when the motor speed is down

The torsional vibration signal which is the vibration signals of rotor speeding down is verified below (see Figure 11 and Figure 12).

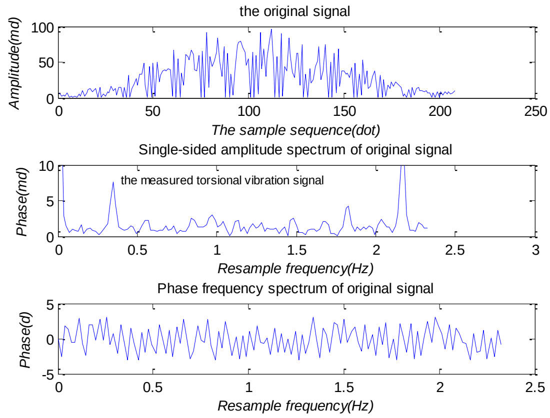

Figure 11. FFT spectrum of the actual acquisition torsional vibration signal

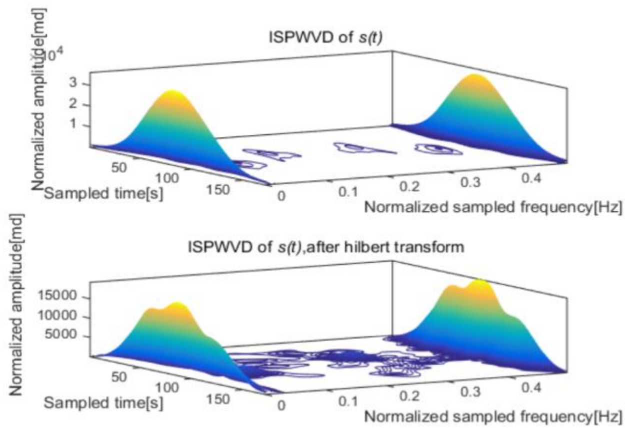

Figure 12. ISPWVD spectrum of the actual acquisition torsional vibration signal

Analysis steps:

Step (1) First, the data becomes smooth, with the purpose of eliminating the irregular trend.

Step (2) Then, the signal is multiplied by a windowed function in order to reduce the spectrum leakage.

Step (3) Then, the data was processed by using the Hilbert transform. Based on the Hilbert transform, the analytic signal is formed.

Step (4) Then, ISPWVD spectrum analysis of the data was done by using the Improvement Smoothed Pseudo.

5. Conclusions

At present, the concrete implementation of the waterfall figure need not only the sensor which is used to measure acceleration, velocity and displacement, but also tachometer which is used to measure the rotor rotation speed, which is for providing reference shaft speed information. This makes that the waterfall figure analysis required measurement process is more cumbersome, especially in the occasion that the tachometer is inconvenient to install.

The ISPWVD spectrum that can be seen from the above may be equivalent to the order spectrum synthesis. Implementation method of a waterfall figure of the vibration analysis may be completed by using above method. Its advantage is to reduce the hardware requirements for realizing the waterfall chart.

References

[1] G.Matz, F. Hlawatsch, Wigner distributions (nearly) everywhere: time-frequency analysis of signals, systems, random processes, signal spaces, and frames, Signal Processing 83 (2003) 1355–1378.

[2] L. Cohen, Time-frequency distributions-A review, in Proc. IEEE 77 (1989) 941–981.

[3] B. Boashash, Note on the use of the Wigner distribution for time-frequency signal analysis, IEEE Transactions on acoustics, speech, and signal processing 36 (1988) 1518–1521.

[4] L. Stanković, A measure of some time-frequency distributions concentration, Signal Process 81 (2001) 621–631.

[5] S-C. Pei, JJ. Ding, Relations between Gabor Transforms and Fractional Fourier Transforms and their applications for Signal Processing, Time frequency complexity and information, IEEE Trans. Signal Process 55 (2007) 4839–4850.

[6] R.G. Baraniuk, D.L. Jones, A signal dependent time-frequency representation: optimal kernel design, IEEE Trans. Signal Process,41(1993)1589-1602.

[7] R.G. Baraniuk, D.L. Jones, Signal-dependent time-frequency analysis using radially-Gaussian kernel, IEEE Trans. Signal Process 32 (1993) 263–284.

[8] E. P. de souza Neto, M. A. Custand, J. Frutoso, L. Somody, Cl. Gharib, J-O. Fortrat, Smoothed pseudo Wigner Ville distribution as an alternative to Fourier transform in rats, Autonomic Neuroscience: Basic and Clinical. 87 (2001) 258–267.

[9] E. Chassande-Mottin, P. Flandrin, On the time frequency detection of chirps1, Applied and Computational Harmonic Analysis 6 (1999) 252–281.

[10] F. Hlawatsch, R. L. Urbanke, Bilinear Time frequency representations of signals: the shift-scale invariant class, IEEE transactions on signal processing 42 (1994)16–32.

[11] F. Hlawatsch, W. Kozek, Time-Frequency Projection Filters and Time-Frequency Signal Expansions, IEEE TRANSACTIONS ON SIGNAL PROCESSING, VOL. 42, NO. 12, DECEMBER (1994) 3321–3334.

[12] D.L. Jones, R.G. Baraniuk, An adaptive optimal-kernel time-frequency representation, IEEE Trans. Signal Process 43 (1995) 2361–2372.

[13] Zh. Qiang, W. Yansong, Sh. Gongqi, Research and comparison of time frequency techniques for nonstationary Signals, Journal of computers 7 (2012) 954–958.

[14] E. Ebrahimzadeh1, S.M. Alavi, A. Bijar, A. Pakkhesal, A novel approach for detection of deception using Smoothed Pseudo Wigner-Ville Distribution (SPWVD), Biomedical Science and Engineering 6 (2013) 8–17.

[15] S. Rajagopalan, Th. G. Habetler, R. G. Harley, J. M. Aller, J. A. Restrepo, Diagnosis of Rotor Faults in Brushless DC (BLDC) Motors Operating Under Non-Stationary Conditions Using Windowed Fourier Ridges, Industry Applications Society 40th Annual Meeting (IEEE IAS2005), Hong Kong, on October 3 (2005).

[16] S. Rajagopalan Thomas, G. Habetler Ronald, G. Harley, J.A. Restrepo, J. M. Aller, Non-Stationary Motor Fault Detection Using Recent Quadratic Time-Frequency Representations, IEEE Transactions on industry applications 44 (2008) 2332–2339.