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Mixed Programming Realization of the EMD-WVD Combined Method

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Abstract

Wigner-Ville Distribution (WVD) possesses high time-frequency concentration and resolutions, but brings serious cross-terms in process of a multi-component signal to distort greatly the result of time-frequency analysis. Because of this the use of the WVD is limited for many applications. In this paper a combined method is proposed: Empirical Mode Decomposition (EMD) is first used to decompose the original signal into a series of Intrinsic Mode Functions (IMFs), then false IMFs among them are eliminated according to the correlation coefficients between each IMF and the original signal, WVD is utilized to analyze the remanent IMFs, finally each WVD is added linearly with together to reconstruct the whole WVDs of the original signal. In order to carry out and validate the combined method, a time-frequency analytic system is designed and realized by using MATLAB and Delphi mixed programming based on COM (Component Object Model) module technology. This system is used to perform vibration signal time-frequency analysis of a grinding machine. The analytic results show validity of the combinedl method and success of the mixed programming.

Keywords: *empirical mode decomposition, wigner-ville distribution, mixed programming, time-frequency analytic system, grinding machine*

1. Introduction

In order to extract the fault features and then identify the fault patterns, signal analysis has been an important topic in mechanical fault diagnosis research and applications. One of the most popular transforms known to scientists and engineers is the Fourier transform that converts a signal from the time domain to the frequency domain. What the spectrum computed by using the Fourier transform tells us are the frequencies contained in the entire time waveform, not the frequencies at a particular time instant. The Fourier transform provides the signal's average characteristics and smears the signal's local behavior. This is the shortcoming of the Fourier transform that has been recognized for a long time. In the process of the machinery fault diagnosis, the signals under considerations are known to be non-stationary, for which the signal's parameters are time-varying. For the spectral analysis of such type of signals, the joint time-frequency analysis technique is widely used. Wigner–Ville distribution is one of the best known analytic tools [1-3].

WVD is a quadratic form time-frequency distribution with infinite resolutions in both the time and frequency domain. And it supplies high resolutions and instantaneous power density spectrums in the time and frequency domain. WVD being quadratic in nature introduces cross-terms because of a multi-component signal. The cross-terms are the main obstacle preventing the use of the WVD for many applications. In order to suppress or delete the cross-terms, Smoothed Pseudo WVD (SPWVD) and Choi-Williams distribution (CWD) etc. appear, using kernel window functions [4, 5]. But these methods reduce the time-frequency concentration. In order to solve the WVD cross-term problem, an effective way is proposed that a reasonable decomposition method is applied to divide a multi-component signal into a number of independent components, then WVD is applied to analyze each single component, finally all WVDs are added linearly with together to reconstruct the original signal time-frequency analysis. EMD can be able to decompose the original signal into a series of independent and local characteristic time scale intrinsic mode functions(IMFs) that are orthogonal to each other [6]. The above method is just the combined method of EMD and WVD to be used to carry out

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vibration signal time-frequency analysis for a grinding machine with high noise. Through comparison of analytic results of FFT, WVD, SPWVD and the combined method, the combined method can get best characteristic information of time-frequency analysis.

In order to perform the above several methods and display their analytic graphics in Windows Operation System, a time-frequency system is designed and implemented by using MATLAB and Delphi mixed programming based on COM module technology. Matlab is a computing science engineering language with high efficiency. It possesses such many advantages that other languages can't match in aspects of matrix algorithm, numerical calculating, signal processing, system identifying, control engineering, neural network, graphics display etc. Now it becomes an essential tool software for researchers. But Matlab is weak in information alternation, program execution, parameters input and output. Delphi is a powerful object-oriented language with many advantages such as rapid development, convenient use, implement of a perfect interface etc.. But Delphi is found so difficult to carry out numerical calculating and graphics processing that its efficiency is much lower than Matlab's in these two aspects. If the two languages are combined to program, they can share and exchange many advantages for each other [7, 8].

2. Cross-terms of Wigner-Ville Distribution

The WVD of a continuous signal x(t) is defined as:

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

If $x(t) = x_1(t) + x_2(t)$, the corresponding. WVD can be rewritten as :

$$WVD_x(t, f) = WVD_{x1}(t, f) + WVD_{x2}(t, f) + 2\,\mathrm{Re}\{WVD_{x1,x2}(t, f)\} \tag{2}$$

According to Equation (2), obviously, except two auto-terms WVD also has one cross-term twice the auto-term. This bad cross-term makes time-frequency analysis of great confusion. In order to reduce or delete the effect of the cross-term, a smoothed window function called a kernel function is brought into the WVD formula, such as smoothed pseudo Wigner-Ville distribution and Choi-Williams distribution and so on appear [9].

3. Principle of Empirical Mode Decomposition

The Empirical Mode Decomposition (EMD) proposed by Huang in 1998 is a very powerful signal analysis tool for both linear and nonlinear cases. The EMD has the ability to decompose any time series into a number of spectrally independent oscillatory modes, called Intrinsic Mode Functions (IMFs). IMFs represent simple oscillatory modes embedded in the signal. Generally, IMFs are orthogonal to each other, and all the IMF's contain only one instantaneous frequency [10, 11]. The IMF should satisfy two definitions:

(1) In the whole analysis dataset, the number of extreme and the number of zero-crossings must be either equal or differ at most by one.

(2) At any point, the mean value of the envelope defined by local maxima and the envelope defined by the local minima is zero.

EMD is applied to decompose the signal x(t) into a series of mono-component Intrinsic Mode Functions, and x(t) can be written as:

$$x(t) = \sum_{i=1}^{n} imf_i(t) + r_n(t) \tag{3}$$

Here $r_n(t)$ is the residue and represents the mean signal's trend.

4. EMD and WVD Combined Method

In process of EMD, there exists over decomposition owing to some following causes: errors in the local average calculation, effect of boundary reaction and undemanding standard for ultimate filtration etc. Over decomposition leads to additional IMFs that do not belong to those of the original signal. The additional IMFs are called “false IMFs” [12]. In order to solve this problem, this paper presents a method that each IMF is used to correlate with the original signal to gain own correlation coefficient. False IMF is eliminated when its correlation coefficient is very small.

In the above formula (3), n IMFs are divided into k basic IMFs and m false IMFs due to over decomposition. The formula (3) can be written as:

$$x(t) = \sum_{i=1}^{n} imf_i(t) + r_n(t) = \sum_{j=1}^{k} c_j(t) + \sum_{l=1}^{m} c_l^{'}(t) + r_n(t) \tag{4}$$

Here $n = k + m$, $\sum_{j=1}^{k} c_j(t)$ represents the sum of k basic IMFs, $\sum_{l=1}^{m} c_l^{'}(t)$ depicts the sum of m false IMFs and $r_n(t)$ is the residue. Obviously the correlation coefficients between the last two terms and the original signal are about zero. The false IMFs and the residue can be ignored due to their much low effect during the process of WVD analysis. The original signal x(t) is approximately combined with the basic IMFs written as :

$$x(t) \approx \sum_{j=1}^{k} c_j(t) \tag{5}$$

Now $c_p(t)$ (p≤k) among the k basic IMFs is used to correlate with the original signal x(t). The formula is written as:

$$\begin{aligned} R_{x,c_p}(\tau) &= E[x(t)c_p(t+\tau)] = E[\sum_{j=1}^{k} c_j(t)c_p(t+\tau)] \\ &= E[c_1(t)c_p(t+\tau)] + E[c_2(t)c_p(t+\tau)] + \cdots + E[c_k(t)c_p(t+\tau)] \\ &= R_{c_p,c_p}(\tau) + \sum_{j=1, j\neq p}^{k} R_{c_j,c_p}(\tau) \approx R_{c_p,c_p}(\tau) \end{aligned} \tag{6}$$

$\sum_{j=1, j\neq p}^{k} R_{c_j,c_p}(\tau) \approx 0$,because the different basic IMFs are orthogonal to each other.

Equation (6) shows that the cross-correlation function between each basic IMF and the original signal is just the self-correlation function of each self basic IMF. The cross-correlation coefficient between the jth basic IMF and the original signal is written as:

$$\rho_{x,c_j} = \left| \frac{E[(x(t)-\mu_x)(c_j(t)-\mu_{c_j})]}{\sigma_x \sigma_{c_j}} \right| \tag{7}$$

Here μ_x, μ_{c_j} respectively represent mean value of the original signal and mean value of the jth basic IMF. σ_x, σ_{c_j} respectively represent variances of the original signal and variances of the jth basic IMF. Obviously, $0 \le \rho_{x,c_j} \le 1$. When ρ_{x,c_j} =0,it shows that the original signal doesn’t any correlate with the jth basic IMF. When ρ_{x,c_j} =1, it depicts that the original signal completely correlates with the jth basic IMF. Thus ρ_{x,c_j} can be used to judge which basic IMF is considered as false IMF or not. If certain false IMFs among k basic IMFs are eliminated, there exists L (L≤k) remanent basic IMFs. The original signal is simply written as:

$$x(t) \approx \sum_{l=1}^{L} c_l(t) \tag{8}$$

The WVD of the original signal can represents as:

$$WVD_x(t, f) = WVD_{c_1}(t, f) + WVD_{c_2}(t, f) + \cdots + WVD_{c_L}(t, f) = \sum_{l=1}^{L} WVD_{c_l}(t, f) \tag{9}$$

5. Realization of the Time-frequency Analytic System

5.1. Mixed Programming

COM supplies with an object-oriented and expanded communication protocol for Windows Operation System. It is a common object interface. According to the interface standard, any language can call it [13]. Firstly programming algorithms of signal analytic methods must be edited into function files (M files) stead of script files using the Matlab M file editor. Then each M file is transformed into different DLL file with the help of Matlab COM Builder in possession of an external compiler such as Borland (3, 4, 5, 6), Microsoft Visual Studio (5.0, 6.0) and Microsoft Visual Studio.Net etc. Microsoft Visual Studio 6.0 is chose in this paper. Finally the each DLL file as type library is assembled into an active-X component in Delphi. The components are put together in a designed interface of the time-frequency system. Through the interface, the components cooperate with each other to interact. When analytic methods are needed to expand, the whole system will not be changed, only the corresponding components will be placed to reassemble the new upgrade analytic functions. Furthermore this system can be executed in Windows separating from the Matlab environment. Figure 1 shows the frame of the programming flow

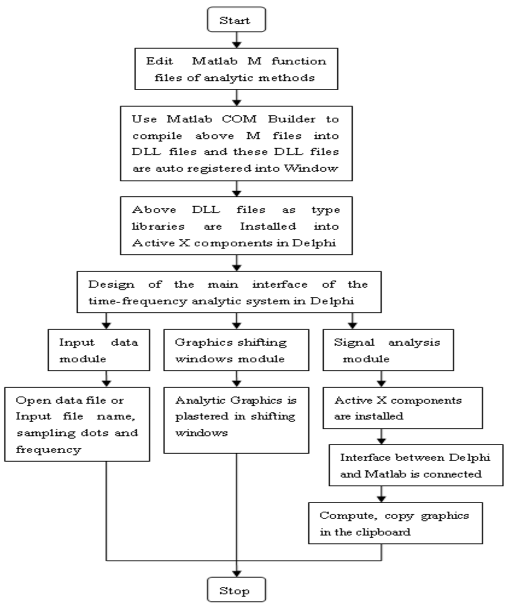


Figure 1. Frame of Programming Flow

5.2. Design of the Main Interface

Figure 2 presents the main interface of the time-frequency analytic system. It is made up of three modules: “input data”, “signal analysis” and “Graphics shifting windows”.

The first module is combined with three sections: input sampling data file includes file path and file name, input data length (sampling data dot), input sampling frequency (Hz). Delphi uses these data to be in communication with Matlab.

The second module is composed of six functions: waveform display, FFT, WVD, SPWVD, EMD-WVD (the combinational method of EMD and WVD) and ALLWVD (All WVDs of true basic IMFs). When programming, the six corresponding Active X components that have been installed above are put into the main interface. Finally the main program is compiled into an executed file that can be separated from Matlab.

In the last module, a window is set up combined with Delphi Panel and Image components. After certain analytic item is clicked in signal analysis module with a mouse, an analytic graphics will be displayed in graphics shifting windows. The graphics can be shifted when a new analytic item is changed.

Figure 2. Main interface of system

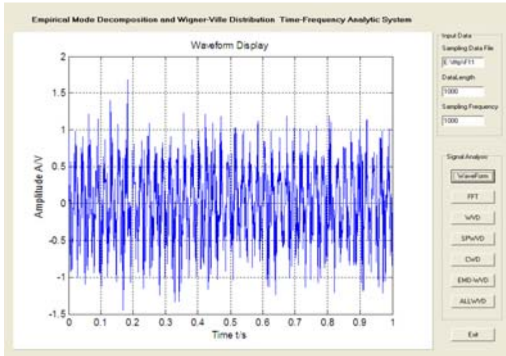


Figure 3. Real time waveform

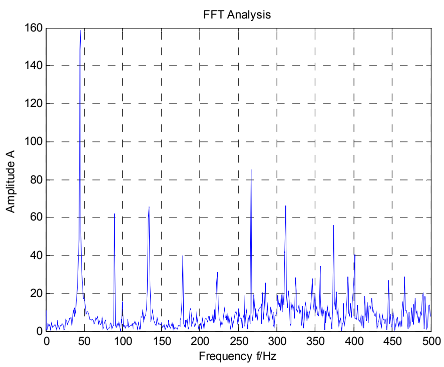
6. An Actual Example

6.1. Signal Sampling

In order to verify effectiveness of the proposed combined method and the time-frequency analytic system, they were evaluated using the real vibration data measured in a type S3SL grinding machine which runs in speed 2850rpm/m (the rotate frequency f0=47.5Hz) with big vibration and noise. A vertical vibration signal is picked up from its surface shell using a type YD-12 accelerometer. A test system consists of type YD-12 accelerometers, a type DHF-4 charge amplifier with filter, a type PCI2006 data sampling card, a computer and a software of vibration signal continuous large data acquisition and processing etc. Figure 3 displays a real time waveform with 1000Hz sampling frequency and 1000 sampling data dots.

6.2. Signal Analysis Using FFT and WVD

The above waveform is analyzed with the Fast Fourier Transform. Figure 4 (This figure and the following figures only display analytic graphics in the scope of shifting windows, cutting the other parts of the main interface) shows the spectrum of the waveform. In the figure, obvious peak values are found out to occur in 1f0, 3f0 positions of low frequency, but bad characteristic information appears in the high frequency scope due to existence of noise. From figure 5a WVD time-frequency analytic graphics, 1f0 characteristic frequency is striking, but others are too difficulty to distinguish as a result of WVD's cross-term leading to wrong estimation.



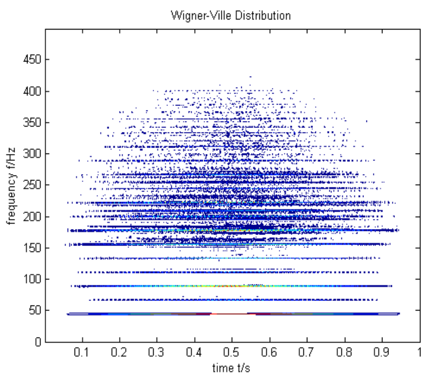


Figure 4. Spectrum of Waveform

Figure 5. WVD Analytic Result

6.3. Analysis of Combined Method of EMD and WVD

Figure 6 shows EMD results, each WVD result of IMFs and correlation coefficients between each IMF and the original signal. The correlation coefficients (IMF1-IMF7) respectively present: 0.6057, 0.2971, 0.5876, 0.2078, 0.0129, 0.0062, 0.0069. Obviously, the last three correlation coefficients are very small, to show that IMF5,IMF6 and IMF7 are consider as “false IMFs” and their corresponding WVD values are about zero. Of course, the WVD of the residue representing the mean trend of the original signal is also considered as zero. WVDs will be performed only for the four remanent IMFs (IMF1-IMF4). All above analytic results can be seen in Figure 6. Finally the four WVDs are added linearly together to get the all WVDs displayed in Figure 7.

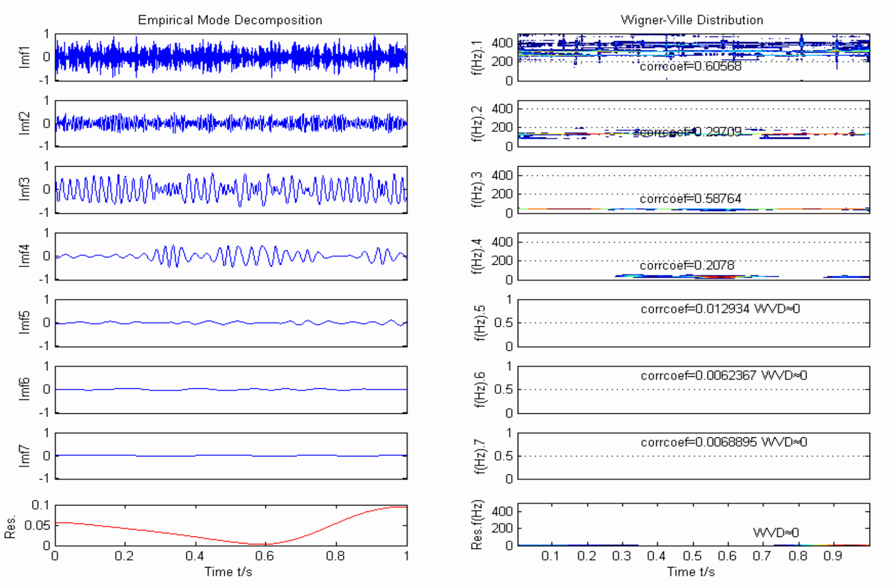
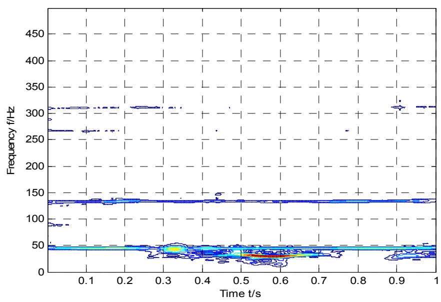


Figure 6. EMD Results, each WVD result of IMFs, correlation coefficients between each IMF and the original signal



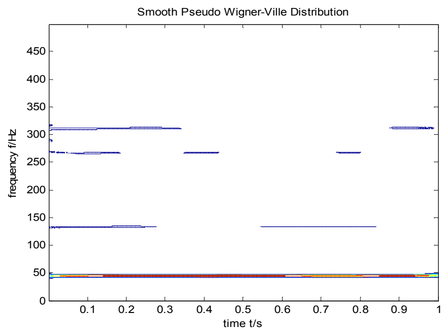


Figure 7. All WVDs Result

Figure 8. SPWVD Result

Figure 7 compares with Figure 8 which shows result of smoothed pseudo Wigner-Ville distribution. It is obviously found that 3f0 characteristic frequency of Figure 7 is much more striking than that of Figure 8. This shows that SPWVD smears partly the 3f0 characteristic frequency which represents certain information of grinding machine vibration. There exist some low varying frequencies (less than 1f0) in scope of about time 0.3-0.75s in Figure 7. This show that the grinding machine vibration signal implies some low frequency information (less than 1f0), but there don't in Figure 8. In two figures, there is an obvious common 1f0 characteristic frequency. The above analytic results reveal that SPWVD suppresses the cross-term of WVD but reduces the time-frequency concentration to smear some information. In Figure7, the analytic result of the EMD-WVD combined method clearly illustrates that the biggest proportion of the characteristic frequency is in the position of 1f0, the second is in that of 3f0, the follow is in that of 7f0.This phenomena demonstrates that the sampled signal of the grinding machine is a modulated signal with certain odd frequencies. According to the relational theory of rotating machinery fault diagnosis [14], this grinding machine comes forth a serious imbalance fault, particularly a bad eccentricity of the grinding wheel that leads to big vibration and noise in the above rotating speed.

7. Conclusions

The EMD-WVD combined method that used to perform time-frequency analysis not only suppresses the serious cross-terms of WVD due to a multi-component original signal but also holds good time-frequency concentration and resolutions. This method effectively overcomes the shortcomings of decrease in time-frequency concentration caused by such as pseudo WVD, smoothed pseudo WVD and Choi-Williams distribution etc. Thus it is a valid method of time-frequency analysis. Through mixed programming of Matlab and Delphi based on COM module technology, a novel programming thought has been revealed in the process of design and implement of the time-frequency analytic system in which is put FFT, WVD, SPWVD, EMD-WVD and ALLWVD functions together. With the help of the new thought, there exist a lot of strongpoints in development of virtual instrument. New analytic components can be easily upgraded to add in this system building up a large system with much more analytic functions. This time-frequency analytic system in possession of the above methods has been applied to carry out the vibration signal time-frequency analysis of a grinding machine. The analytic results validate the success of mixed programming with COM module technology.

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