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APPLICATION OF WAVELET TIME-FREQUENCY ANALYSIS ON FAULT DIAGNOSIS FOR STEAM TURBINE

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Abstract:

Many vibration signals of fault turbine rotor are nonstationary and have highly complex time-frequency characteristics. A good way to analyze the nonstationary mechanical signals is the wavelet transform. Unfortunately, the direct result of wavelet transform in fault diagnosis of steam turbine is not easy to understand because it lack of physical meaning compared with FFT. Consequently, time-frequency contour map is introduced into fault diagnosis of steam turbine. The time-frequency contour map can easily show the power distribution of signal in time and frequency domain. Moreover, it is a good way to identify the steam turbine faults involving a breakdown change. Six typical faults of steam turbine are discussed by the time-frequency contour map in the paper. The simulative results show that time-frequency contour map have the capabilities to identify the difference of those faults of steam turbine. In conclusion, the faults of steam turbine can be classified by time-frequency contour map.

Key word: time-frequency analysis, wavelet, fault diagnosis, steam turbine

1. Introduction

In order to increase the availability of steam turbine, the technique of vibration diagnosis has been widely used for many years as a tool for the detection of machine faults and has shown its advantages in many aspects. For example, with the help of the vibration analysis it is possible to detect a fault of steam turbine at an early stage before the fault develops to an eventual failure and interrupts the production process. Its application saves a large amount of time for machine maintenance and reduces the production losses greatly. The vibration diagnosis is normally carried out in the following main steps: signal measurement, signal analysis, diagnosis and strategic decision, where the signal analysis plays a key role and has the task of extracting useful information, filtering noise from a measured vibration signal and finding the fault feature and its developing trend. Traditional spectral analysis techniques, based on the Fourier transform provide a good description of stationary and pseudo stationary signals. Unfortunately these techniques have several shortcomings. First of all, the Fourier transform is unable to accurately analyze and represent a signal that has non periodic components, such as a transient signal (impulses). This is due to the fact that the Fourier transform is based on the assumption that the signal to be transformed is periodic in nature and of infinite length. Another deficiency of the traditional spectral analysis is its inability to provide any information about the time dependency of the frequency contents. This becomes a problem when the signals to be analyzed are highly non stationary. In this case it is especially beneficial to be able to acquire a correlation between the time and frequency domain of a signal. In practice there are many cases for steam turbine fault diagnosis, where the duration of a vibration signal is very short and/or the frequency information changes with time. Therefore in recent years there has been an increasing interest in the research of signal analysis concerning the time-frequency domain. The development of the time-frequency analyses is motivated by the desire to overcome the drawbacks of the conventional Fourier transform. The time-frequency analyses are able to analyze a non stationary signal and it indicates not only which frequencies the signal contains, but also when these frequencies occur.

In principle there are two basic approaches to analyze a non stationary vibration signal in time and frequency domain simultaneously. One approach is to split a non stationary vibration signal at first into segments in time domain by proper selection of a window function and then to carry out a Fourier transform on each of these segments separately and deliver an instantaneous spectrum. This is the basic idea for the calculation of the short time Fourier transforms (STFT). Wang has claimed the Short Time Fourier Transform (STFT) to be a powerful tool in detecting local gear damage at an early state [1]. According to one study, STFT will perform better here than conventional methods [2]. Others have investigated STFT methods for the early detection of faults in gears [3, 4]. While the STFT compromise between time and frequency information can be useful, the drawback is that once you choose a particular size for the time window, that window is the same for all frequencies. Many signals require a more flexible approach — one where we can vary the window size to determine more accurately either time or frequency.

The other approach is the so called wavelet transform (WT), where the non stationary vibration signal to be analyzed is filtered into different frequency bands, which are split into segments in time domain and their frequency contents and energy are analyzed. Wavelet analysis overcomes the disadvantage of STFT since WT uses a windowing technique with variable-sized regions. Wavelet analysis allows the use of long time intervals where we want more precise low-frequency information, and shorter regions where we want high-frequency information. The definition of the continuous wavelet transform (CWT) is written by:

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int s(t) \bullet \psi * (\frac{t-b}{a}) dt$$

Where $s(t)$ is the signal to be analyzed and $\psi(t)$ is called the mother wavelet or basic function, * denotes the complex conjugate, a is the scale variable ($a \neq 0$), and b the time shift variable. During the analysis the wavelet is transformed in time to select the part of the signal to be analyzed by using b , then dilated/expanded or contracted/compressed by using a in order to focus on a given range or number of oscillations. When the wavelet is expanded, it focuses on the signal components with low frequencies and when compressed on the components with high frequencies. Due to the compression and expansion of the wavelet, the WT performs a time scale decomposition of the signal s(t) into a weighted set of scaled wavelet functions. Wavelet analyze is used in the paper [5] to detect the fault of fans and the signal component indicative of a fault was identified from the sound signals. A method is proposed in the paper [6] for the analysis of vibration signals resulting from bearing with localized defects using the wavelet packet transform as a systematic tool. The methods of wavelet analysis with ED are proven to be efficient in detecting some types of rolling element bearing faults

[7]. The paper [8] reports the study of four time-frequency transforms applied to vibration signals and presents a new metric for comparing them for fault detection. Furthermore, analysis with the CWT detects gear problems not found with the other transforms [8].

Unfortunately, the direct result of wavelet transform in fault diagnosis of steam turbine is not easy to understand because it lack of physical meaning compared with FFT. As a consequence, time-frequency contour map is introduced into fault diagnosis of steam turbine. First, Continuous Wavelet Transform is used to analyze the fault signal and 3 dimensions Time-scale plot can be done. Secondly, 3 dimension time-scale plots are converted to time-frequency contour map by a given arithmetic. The time-frequency contour map can easily show the power distribution of signal in time and frequency domain. Moreover, it is a good way to identify the steam turbine faults involving a breakdown change.

All below results are computed in Matlab environment since it is very easy to program and do scientific calculation.

2. Selection of mother wavelet function

The correct selection of the analyzing wavelet with different properties is of critical importance for enhancing the fault features in the wavelet analysis. Various wavelets are available for wavelet applications. Some of them have a good time–frequency localization property which is a desirable attribute for fault detection applications. In this work, four different analyzing wavelets, Morlet, Mexican hat, Discrete Meyer and the Gaussian wavelet were initially examined for their performance in detecting fault conditions in the steam turbine. The best performance was obtained from the Complex Morlet wavelet although the Gaussian wavelet also generated good results for the analysis. Therefore, all the results of the wavelet analysis in this study were based on the Complex Morlet wavelet. The advantage of the proposed wavelet in this work is that harmonic frequency can also be easily controlled by the correct selection of F_c, and not only the scale parameter a. Consequently, this provides extra flexibility to obtain a good time–frequency resolution.

The definition of Complex Morlet wavelet function is :

$cmor(x) = \frac{1}{\sqrt{\pi F_b}} e^{2i\pi F_c x} e^{-x^2 / F_b}$ .It depends on two parameters : F_b is a bandwidth parameter, and F_c is a wavelet center frequency. Figure 1 shows the characteristic of Complex Morlet wavelet function.

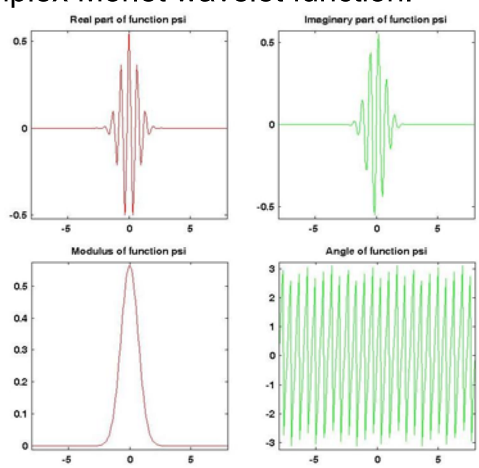


Figure 1 complex Morlet function

3. Conversion scale to frequency

The result of wavelet transform is not easy to be understood by engineer compared with the FFT result. A common question is what is the relationship between scale and frequency? The answer can only be given in a broad sense, and it's better to speak about the pseudo-frequency corresponding to a scale. A way to do it is to compute the center frequency *Fc* of the wavelet and to use the following relationship.

$F_a = \frac{F_c}{a \bullet \Delta}$, where

a is a scale.

Δ is the sampling period.

Fc is the center frequency of a wavelet in Hz.

Fa is the pseudo-frequency corresponding to the scale *a*, in Hz.

The idea is to associate with a given wavelet a purely periodic signal of frequency *Fc*. The frequency maximizing the FFT of the wavelet modulus is *Fc*. The figure 2 shows the example of center frequency of complex Morlet wavelet and it plots the wavelet with the associated approximation based on the center frequency.

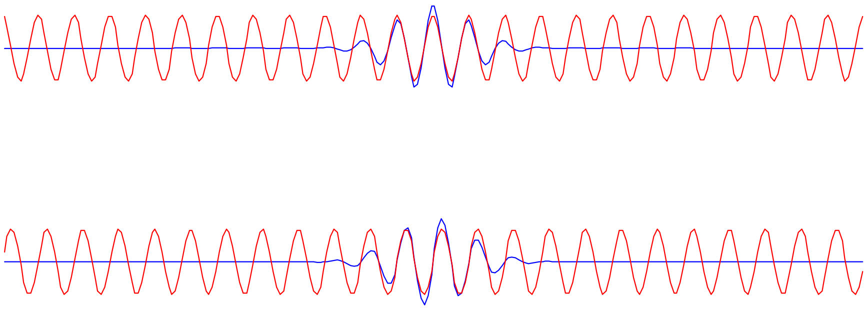


Figure 2 the center frequency of Complex Morlet wavelet

4. Application in fault diagnosis of steam turbine

The wavelet transform is used in diagnosis of steam turbine because it is able to visualize phenomenon in time-frequency domain and to detect the beginning time and the duration of it. Several faults of steam turbine are simulated and discussed in the paper. The time-frequency contour is used to distinguish and classify.

The most commonly fault of steam turbine is unbalance which is showed in figure 3. The upper part of figure 3 is original waveform and the middle one shows the spectrum calculated by FFT. The lower part of figure 3 is the time-frequency contour calculated by wavelet transform. Compared with FFT spectrum , the time-frequency contour shows the similar detail information in the case because the signal is stationary. In this figure, the frequency at which a peak is seen in the spectrum and the power distribution in the time-frequency are roughly the same, and the main frequency component are the frequency of operating frequency.

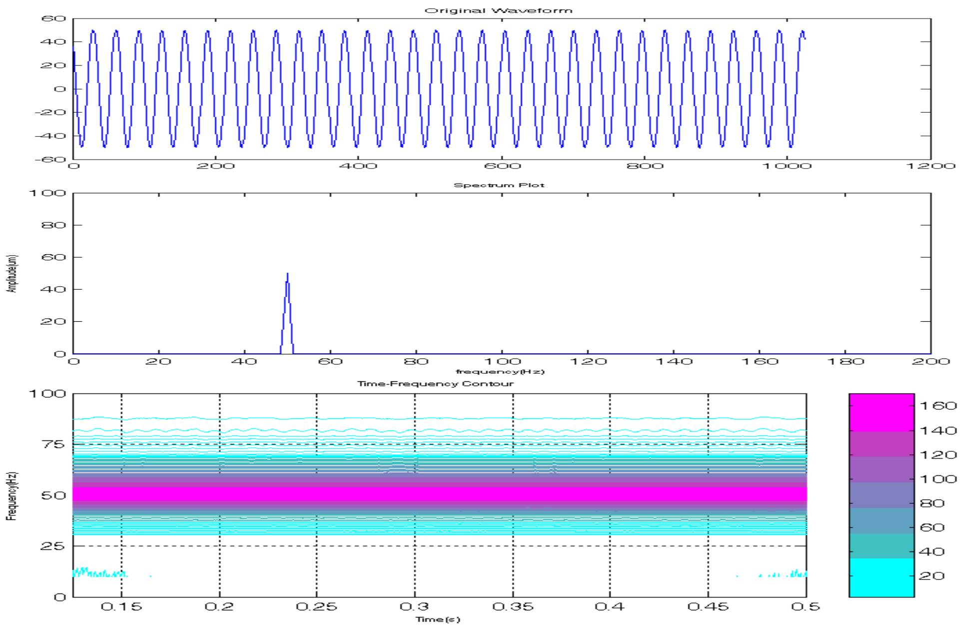
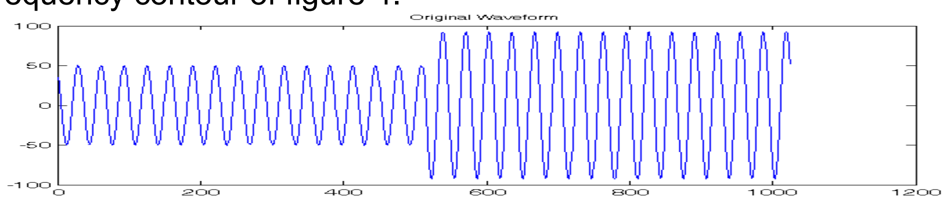


Figure 3 Unbalance

In another faults of steam turbine, obvious advantage of time-frequency contour is displayed since the signal is nonstationary. The next fault of steam turbine is loss of component such as blades. It will cause damage of turbine and performance degradation. Therefore, it is very important to detect the fault at the early stage. The below plot shows the original signal of these fault that is nonstationary signal. It can be seen from spectrum that the main frequency component is 50 Hz which is related to the operating frequency because the FFT just express the statistical average result of frequency domain. From the time-frequency contour, it is easily shown that the power distribution of frequency domain is changed at the midpoint of time domain. Compared with figure 3, the difference of unbalance and loss of component which are similar in the FFT analyses can be easily distinguished by the time-frequency contour. Meanwhile, more detail information can be found from the time-frequency contour of figure 4.



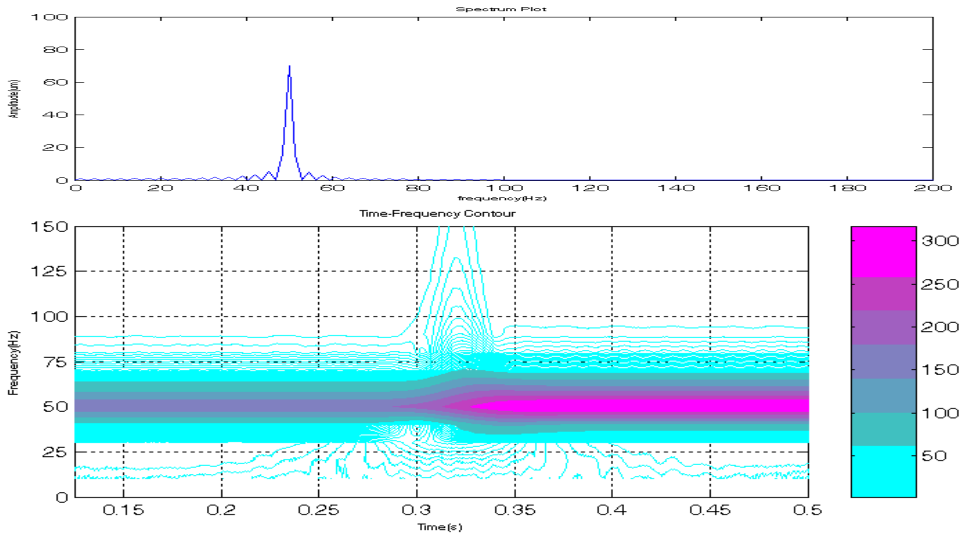
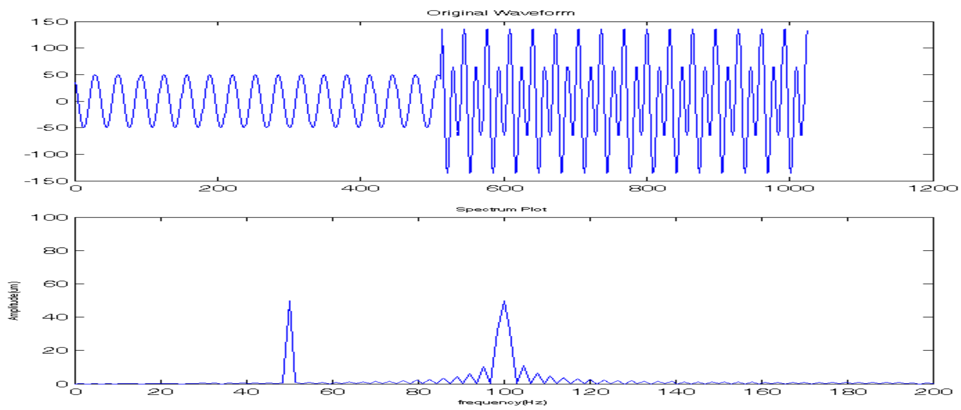


Figure 4 Loss of component

Those above described two faults are commonly emerged in practice of steam turbine and they have the similar symptom when it is analyzed by the FFT. However, the time-frequency contour analyzed by wavelet transform can easily distinguish those two faults because the wavelet has characteristic of the time frequency localization.

The third fault of steam turbine is misalignment. Misalignment is a condition where the centerlines of coupled shafts do not coincide. If the misaligned shaft centerlines are parallel but not coincident, then the misalignment is said to be parallel misalignment. If the misaligned shafts meet at a point but are not parallel, then the misalignment is called angular misalignment. Almost all misalignment conditions of machines seen in practice are a combination of these two basic types. And misalignment diagnosis is based on stronger 2X peaks than 1X peaks and the existence of 1X and 2X axial peaks. From the below figure 6, it can be seen that both FFT analyze and time-frequency contour can diagnose this fault, while time-frequency contour can provide more time information of occurrence.



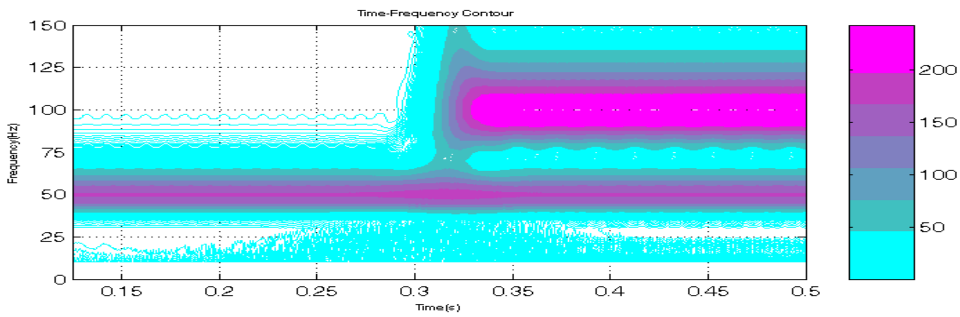


Figure 5 Misalignment

The fourth fault of steam turbine is looseness. Looseness between a machine and its foundation will increase the 1X vibration component in the direction if the least stiffness. This is usually the horizontal direction, but it depends on the physical layout of the machine. Low-order 1X harmonics are also commonly produced if the looseness is severe. Foundation flexibility or looseness can be caused by loose bolts, corrosion, or cracking of mounting hardware. The below figure 6 shows the horizontal vibration signal of steam turbine where looseness happens to appear. It is clearly seen that one half, and one third-order harmonics sometimes called sub harmonics are existence. Meanwhile, the exact occurrence moment is also found from the time-frequency contour.

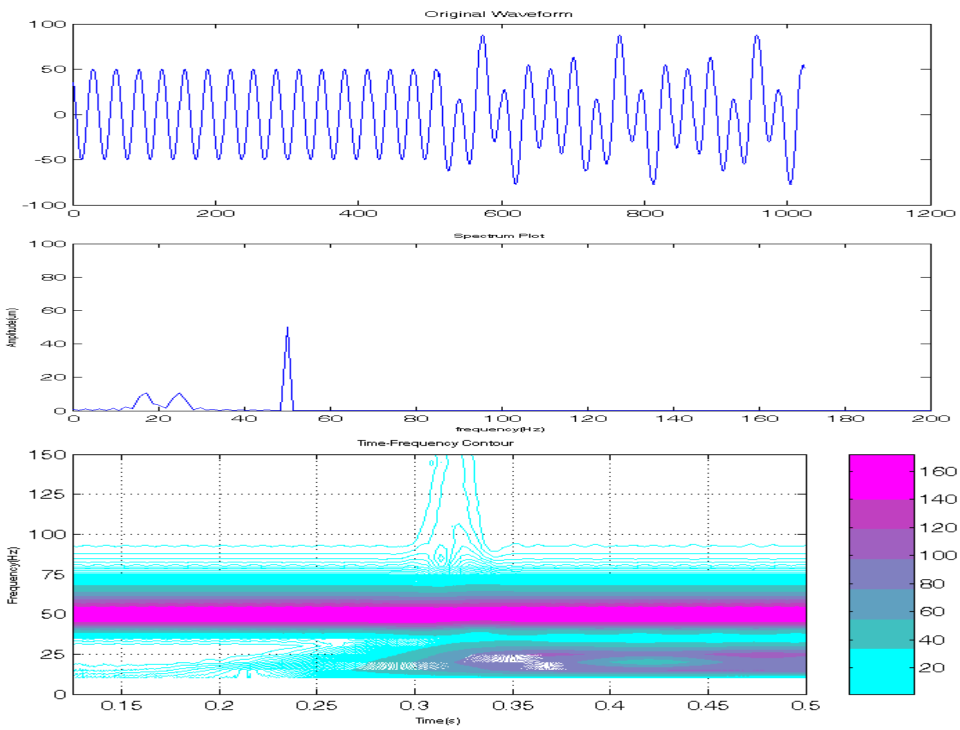


Figure 6 looseness

Most steam turbine is supported by journal bearing. And Oil whip is a severe journal bearing problem. Oil whip is a condition in which a strong vibration occurs at between 0.38X and 0.48X. It never shows up at precisely

0.5X, but is always a little lower in frequency. It is caused by excessive clearance and light radial loading, which results in the oil film building up and forcing the journal centerline to migrate around in the bearing opposite the direction of rotation at less than one-half RPM. Oil whip is a serious condition and needs to be corrected when found, for it can deteriorate fairly quickly to the point where metal-to-metal contact occurs in the bearing. The figure 7 shows the oil whip of journal bearing on steam turbine. And it can be seen that the frequency distribution of this fault changed when oil whip appear.Moreover, the exactly moment of oil whip is easily observed and it is important to take some measures to correct the fault.

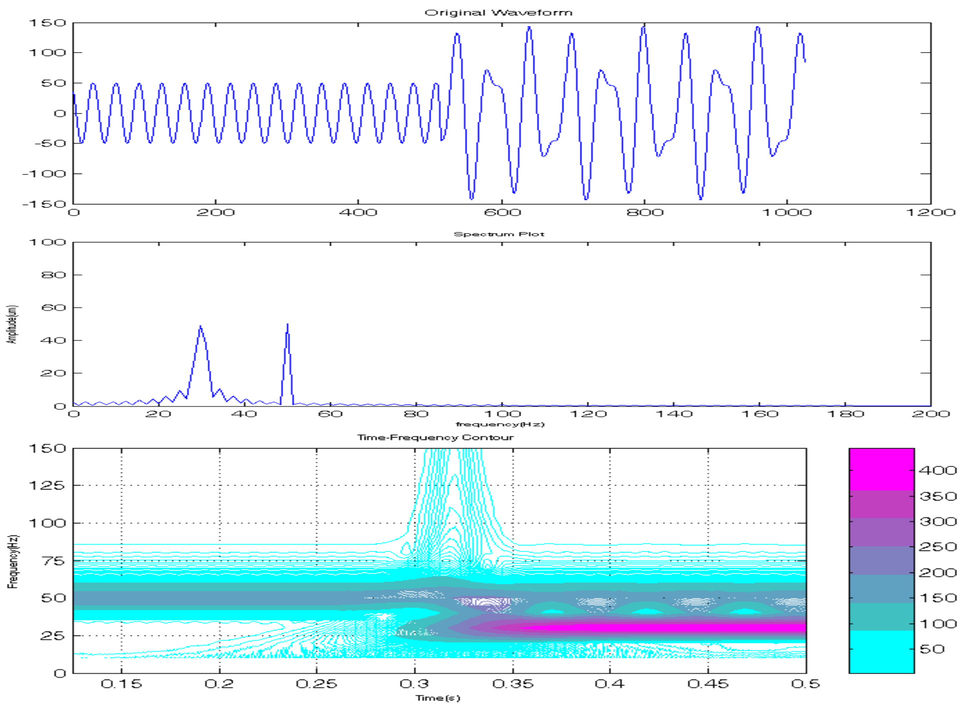


Figure 7 Oil whip

Another common problem in newly rebuilt or modified turbine rotors is a slight rubbing condition as the rotor is initially operated. Rotor rubs are not a phenomenon which continues over an extended period; they usually increase the clearances until the rub has been cleared or, if not corrected, they will wear away the internal clearances until the machine cannot be operated.

Spectra displays of rub conditions are characterized by distinct frequencies that occur at multiples of a fundamental frequency. For the nonlinear characteristic of the rub, the fundamental rub frequency will coincide with the shaft speed with multiples at 2X, 3X, and 1/2 X etc. Similarly, it is easily seen that the frequency and time domain information is simultaneity provided by the time-frequency contour. Consequently, the rub fault of steam turbine can be detected in the early stage to suppress the development of failure.

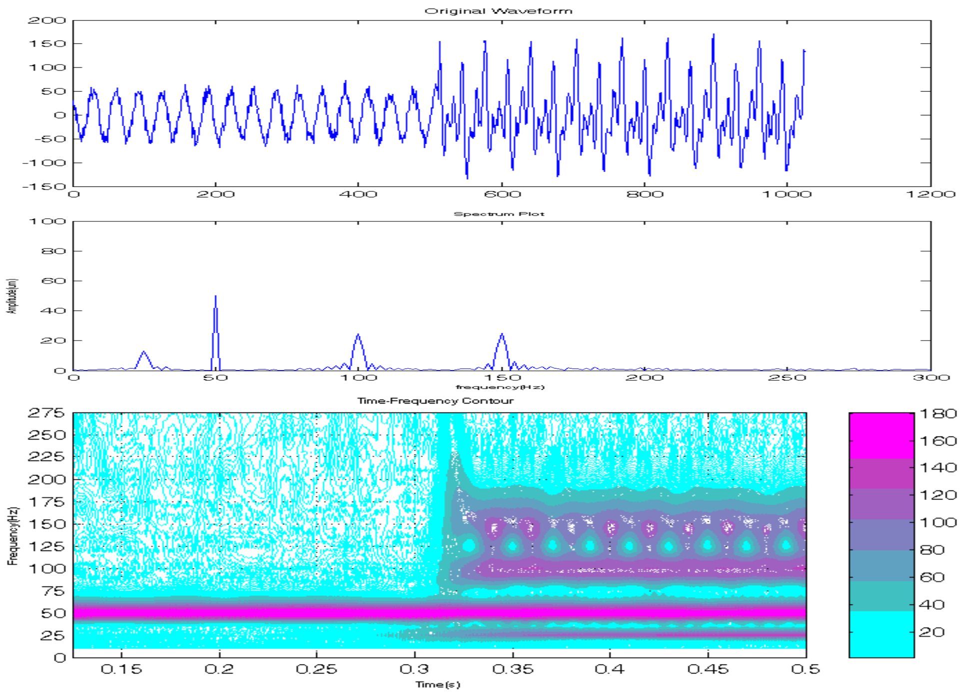


Figure 8 Rub

5. Conclusion

Signal analysis techniques play a key role for fault diagnosis of steam turbine. Traditional spectral analysis techniques provide a good description of stationary signals. However they can not give any information about the time dependency of the frequency contents of a signal. In addition these techniques are also unable to analyze non stationary signals. By contrast, in TSI of Steam Turbine System, the vibration frequencies being measured by probe can change rapidly in time, especially if a fault has occurred. Many types of turbine damage produce localized changes in the signal so that the signal is no longer stationary on the time-scale of the revolution. The signal near the fault may vary considerably from the rest of the signal. If the situation is critical, it is important to determine the severity so that corrective actions can be taken. To solve these problems, time-frequency contour has been introduced and developed into fault diagnosis of steam turbine. Firstly, Wavelet transform are reviewed and discussed in this article. And then the properties of time-frequency contour are presented and discussed. At last, six typical faults of steam turbine are discussed and analyzed in the paper. And it can be proved that time-frequency contour can be used to classify and distinguish the faults of steam turbine. Moreover, time-frequency contour also provide more significant time information of fault than FFT analysis. In general, Simulation results show that the proposed time-frequency contour is effective in both fault detection and diagnosis on steam turbine, illustrating the potentials for real-world application.

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