USING SHORT-TIME FOURIER TRANSFORM IN MACHINERY DIAGNOSIS

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Abstract
Diagnostic of machine using the time-frequency representation of vibration is becoming widely used by many companies and experts. In recent years, the preventive maintenance is no more desirable and in fact it has evolved into the prediction maintenance. The current methods of machine diagnosis can not provide detailed diagnostics and condition prediction.
This paper proposes the application of Short-Time Fourier Transform (STFT) as a time-frequency method, which can provide more information about a signal in time and in frequency and gives a better representation of the signal than the conventional methods in machinery diagnosis.
In this paper, we review the machine diagnosis techniques based on the verification of classical vibration parameters. Then the necessity of using time-frequency analysis in machinery diagnostics is discussed. Finally, the theory of the Short-Time Fourier Transform is briefly studied and its advantages are shown by some practical examples.

1. Introduction

The objective of diagnostic of machine by vibration analysis has been considerably changed. The initial objective was the security of machine against the important damages. If the vibration amplitude (displacement, velocity or acceleration) reaches to the limit value the alarm rings and the machine stops. But to day, our objective is no only to protect the machine but also to detect and identify defaults in the first step to have the necessary time to schedule repairs with minimum disruption to operations and production [1].
Then, the key factor of the prediction maintenance is diagnostic. A diagnosis is not an assumption; it is a conclusion reached after a logical evaluation of the observed symptoms.
In practice, different strategies of maintenance can be observed:
a) Conditional preventive maintenance: an inspection is performed if the surveillance vibration values go beyond the limit values.
b) Systematic preventive maintenance: inspection is periodically performed but the inspection date depends on the old of machine and the life length of the elements of machines.
c) Prediction maintenance: an inspection would have been performed if a defect has already been detected.
There are several conventional methods, which have been applied for a long time to fault detection and identification. Some of these methods provide a representation of signals in time domain and others provide a representation of signals in frequency domain. In all of these methods, it is assumed that signals are stationary but this assumption is not always true. In certain machines when

defects begin, vibration signals become non-stationary and in this case, the conventional methods are not applicable. In recent years, a number of new analysis methods have been developed in the field of signal processing called joint time-frequency analysis methods. But there is a little tendency to use these methods in the field of machinery diagnostics. Mechanical engineers are not well familiar with these methods and some works are necessary to show the true potential of these new methods. The research into the development of the theory of joint time-frequency methods and other non stationary signal processing methods are fast progressing but it seems that some works are needed to motivate the industrial people and show them the capability of these new methods in condition monitoring of mechanical systems. The objective of this work is on the one hand, to express the limitations of the conventional methods and on the other hand, to demonstrate the rapidity and the accuracy which can be obtained by using the joint time-frequency analysis methods in field of machinery diagnostics.

2. Conventional Vibration Analysis Techniques

Overall level measurement [2] is the most common vibration measurement in use. It is a simple and inexpensive type of measurement to undertake. There are charts available which indicate the levels deemed acceptable, for example VDI 2056. The greatest limitation is the lack of sensitivity and information available in the data.

Great many indicators have been also developed for machine condition monitoring and fault detection, such as *crest factor* [3] and *Kurtosis* [4]. Machine monitoring and diagnosis on the basis of variations in the frequency modulation of certain characteristic indicator values of the signal spectrum in large bands and in narrow bands is very unreliable. One reason for this is that it is necessary to define a large number of indicators corresponding to a small number of defects.

In addition, we need to take into consideration not only the increase in the power of the signal, but also the development of its form.

An alternative techniques have been also applied to verifying the variation in the form of a signal such as *Cepstrum* [5] (the inverse Fourier transform of the logarithmic spectrum of the signal) and the *envelop method* [3][6] (Hilbert transform) of the narrow band of the signal.

3. Is the time-frequency analysis necessary?

As mentioned in the last section, each of the conventional vibration methods used in fault detection and identification for steady speed machines has several limitations. The assumption of constant speed in the above methods results in stationary and pseudo-stationary vibration signals. However, even if we take this assumption into account, the limitations of the above methods reduce their performance. On the other hand, there are presently several types of varying and variable speed rotating machinery for which the stationary or pseudo-stationary vibration signals cannot be assumed. The time-frequency analysis not only enables us to represent the signal in three dimensions (time-frequency-amplitude) but also permit us:

a) To detect and follow the development of the defects which generate weak vibration power. However, the weak vibration power can modify the form of the signal to a considerable extent, as happens when defects produce the amplitude modulation or

components. Examples of this are the journal bearing of a shaft with a slow or very slow rotational velocity, a rotating oven, dryer cylinders, the press sections of a paper machine, etc.;

b) To supervise the installations in which the normal functional process produces high amplitude periodic shocks (piston or screw compressor, reciprocating machinery and cam mechanisms, ...) which may mask the faulty frequency producing the impulsive forces. (fault in a bearing, coupling, ...).

The time-frequency methods are regarded as advanced diagnostic techniques, which offer high sensitivity to faults and a good diagnostic capability.

4. Short-Time Fourier Transform

The short-time Fourier transform (STFT) was the first time-frequency method, which was applied by Gabor [7] in 1946 to speech communication.

The STFT may be considered a method that breaks down the non-stationary signal into many small segments, which can be assumed to be locally stationary, and applies the conventional FFT to these segments.

The STFT of a signal $s_t(\tau)$ is achieved by multiplying the signal by a window function, $h(\tau)$, centered at A*t*@, to produce a modified signal. Since the modified signal emphasises the signal around time A*t*@, Fourier Transforms will reflect the distribution of frequency around that time.

$$S_t(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-j\omega\tau} s(\tau)h(\tau - t)d\tau \qquad (1)$$

We may consider $S_t(\omega)$ as the sum of the Fourier base functions but the base functions are a modulated version of the window function.

The energy density spectrum at time A*t*@ may be written as follows:

$$P(t,\omega) = \left|S_t(\omega)\right|^2 = \left|\frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-j\omega\tau} s(\tau)h(\tau - t)d\tau\right|^2 \qquad (2)$$

For each different time we get a different spectrum and the ensemble of these spectra provide the time-frequency distribution $P(t,\omega)$.

Resolutions in time and frequency will be determined by the width of window $h(\tau)$. A large window width is chosen when we need greater accuracy in frequency and a small window width when we want to have greater accuracy in time. However, the STFT depends greatly on the width of the window and by varying the window used, one can exchange resolution in time for resolution in frequency.

5. Industrial application of STFT in mechanical systems

In the last few decades, many methods of time-frequency analysis have been applied to various areas of physics and engineering, such as speech processing and image processing. In the field of machinery diagnostics, Forrester [8] has used time-frequency methods in the detection of damaged gears in helicopter gearboxes. He has shown that, with the signal enhancement techniques (conventional methods) offered by Stewart and McFadden, it is difficult to distinguish one type of fault, e.g. tooth-cracking or pitting, from another; but the time-frequency methods can more accurately reveal the type of defect. Wang and McFadden [9] have also studied the application of time-frequency analysis to the detection of gear damage. They have proven that application of the Spectrogram (STFT) for the early detection of damage in gears has some advantages over the application of other time-frequency methods.

In another work, Rohrbaugh [10] has applied time-frequency analysis to several sets of marine machinery. He compared the

Spectrogram (STFT) with cone-kernel time-frequency representation from Cohen class distributions. He showed that, while the Spectrogram can reveal the general time-varying characteristics of a vibration signal, for more information about the signal we must consider other time-frequency methods. Some applications of time-frequency analysis to the monitoring of machining processes, such as drilling and grinding operations, have been presented by Loughlin, Atlas, Bernard and Pitton [11]. They showed that, although the Spectrogram (STFT) is an efficient method for the demonstration of the time-varying characteristics of a process, sometimes newer time-frequency methods can provide more detail on the signal. They concluded that the newer methods of time-frequency analysis might assist in the early detection of problems. Atlas, Bernard and Narayanan [12] summarized some applications of time-frequency analysis in different domains of machinery diagnostics. They emphasised the importance of using time-frequency analysis in manufacturing and monitoring applications. The papers cited above give some examples of the application of different time-frequency methods, including the STFT, to condition monitoring of mechanical systems. Each of these papers shows the way in which a new time-frequency method can reveal certain information about the signal that can not be obtained by traditional methods.

Today, one of the most important factors limiting the progress of machine diagnostic techniques is the lack of familiarity of mechanical engineers with new signal processing methods. The complicated theory of time-frequency analysis and the absence of operational software for time-frequency analysis restrict engineers from using these

Among the various time-frequency methods, the Short-Time Fourier Transform is the easiest and the fastest method.

This work is an attempt to present the limitations of conventional methods of vibration analysis in machine diagnosis and to emphasise the application of the STFT to fault detection and identification.

A user-friendly software has also been developed to facilitate the use of time-frequency methods by engineers whether or not they are familiar with time-frequency analysis.

Now, the efficiency of STFT for an industrial case without any prediction of defects is demonstrated. This case comes from the defective gear-train of a hoist drum in a large shovel operating at an open-pit iron mine. The data are measured by International Measurement Solutions company in order to find the problem in the machine.

Gears generate a mesh frequency equal to the number of teeth on the gear multiplied by the rotational speed of the shaft driving it. A high vibration level at the mesh frequency is often caused by tooth error, wear of the meshing surfaces, or any other problem that would cause the profiles of meshing teeth to deviate from their ideal geometry. Sidebands at the mesh frequency, on the other hand, are typically due to a failure of mating teeth. Imagine a cracked tooth, which is not yet broken, and will consequently not be noticed by the operating personnel. However, it will, due to its weakened mechanical condition, deflect more under load than the other (healthy) teeth when it goes into mesh. This results in a signal with amplitude modulation. Thus, an increasing level in the sidebands spaced with rotation speed in the frequency spectrum results from the cracked tooth.

A minimum length of time is required to perform an FFT analysis of each process. The time resolution required will depend on the period of each tooth mesh and the desired

level of accuracy. Sometimes, it is not possible to measure the signal for long enough to provide the periodicity of shock in the FFT spectrum.
In this particular case, the process did not even last one revolution of the driven gear. The case was investigated by time-frequency distribution precisely because it is known that time-frequency methods do not need as much time signal as the FFT spectrum.
Figure 1 shows respectively the signal and its spectrum and its short-time Fourier transform. The spectrum of the signal indicates some large peaks around 200 Hz and some other smaller peaks in the vicinity of 400 Hz, 800 Hz and 1200 Hz. However, it is very difficult to assume or confirm any defects at this point.
On the other hand, The Short-Time Fourier transform clearly displays time-frequency representation of the signal. There are a gear meshing frequency at approximately 220 Hz and some pulses at approximately 440 Hz. It has known that pluses are appeared in the vibration signal of a gearbox if there is a broken tooth.
Then, we may conclude that there is a broken tooth in this gearbox. It is also possible to find the location of the fault in gearbox. The frequency of repetition of the pulses $(\frac{1}{\approx 2.65 \text{ sec}} = 1.5 \text{ Hz})$ determines the rotating speed of the shaft with faulty gear in gearbox. As well as, in frequency domain the frequency of pulses ($\approx$440 Hz) is equal to the meshing frequency of faulty gear.

6. Conclusion

It has been shown that, although the majority of conventional methods may give good results when detecting a single fault in various simple elements of machines, no single technique can provide all the answers for all cases. It is difficult to decide which method gives the best result, in particular when the precise type of fault is not known.
The Short-time Fourier Transform is an effective method of time-frequency analysis and a powerful tool in machine condition monitoring. The short-time spectrum gives a clear representation of the time-frequency plane and a simple interpretation of the energy variation due to damage. There is, unfortunately, a fundamental problem with this approach: high resolution cannot be obtained simultaneously in the time domain and the frequency domain. Although this method gives the time-frequency information with limited precision, but it is better than the conventional methods of machine diagnosis and may be used to present the general time-varying characteristic of a signal.
The development of a user-friendly software package facilitates the use of time-frequency techniques in machine diagnosis. The time-frequency methods, including the short-time spectrum, have been implemented on a computer and used, along with conventional methods, in the analysis of vibration signals. The advantages of the short-time spectrum have been demonstrated by using this method on vibration signals from an industrial gearbox.

7. References

[1] R.G. Smiley, *Rotating Machinery: Monitoring and Fault Diagnosis*, Sound and Vibration, 17(9) (1983) 26.

[2] R. Archambault, *Getting More Out of Vibration Signals: using the logarithmic scale*, Proceedings of the 1st International Machinery Monitoring & Diagnostic Conference & Exhibit, (1989) 567.

[3] A. Barkov, N. Barkova and J.S. Mitchell, *Condition Assessment and Life Prediction of*

Rolling Element Bearing - Part 1, Sound And Vibration, 29(6) (1995) 10.

[4] M.J. Brennan, M.H. Chen and A.G. Reynolds, *Use of Vibration Measurements to Detect Local Tooth Defects in Gears*, Sound and Vibration, 31(11) (1997) 12.

[5] Angelo Martin, *Vibration Monitoring of Machines*, Brueel & Kjaer Technical Review, No. 1, PP 1-36, 1987

[6] R.M. Jones, *Enveloping for Bearing Analysis*, Sound and Vibration, 30(2) (1996) 10.

[7] D. Gabor, *Theory of Communication*, J. IEEE (London), 93 (1946) 429.

[8] B.D. Forrester, *Use of Wigner-Ville Distribution in Helicopter Fault Detection*, Proceeding of Australian Symposium on Signal Processing and Applications - ASSPA 89, Adelaide, PP. 78-82, April 1989.

[9] W.J. Wang and P.D. McFadden, *Early Detection of Gear Failure by Vibration Analysis - I. Calculation of the Time-Frequency Distribution*, Mechanical Systems and Signal Processing, 7(3) (1993) 193.

[10] R. Rohrbaugh, *Application of Time-Frequency Analysis to Machinery Condition Assessment*, Soc. Proceedings of the 27th Asilomar Conference on Signal, Systems & Computer, 2 (1993) 1455.

[11] P. Loughlin, L. Atlas, G. Bernard and J. Pitton, *Application of Time-Frequency Analysis to the Monitoring of Machining*, Life Extension of Aging Machinery and Structures: Proc. of 49th Mtg. of MFPT Soc., Vibration Inst.: Virginia Beach, 49(4) (1995) 305.

[12] L. Atlas, G. Bernard and S.B. Narayanan, *Applications of Time-Frequency Analysis to Signal From Manufacturing and Machine Monitoring Sensors*, Proceedings of the IEEE, 84(9) (1996) 1319.

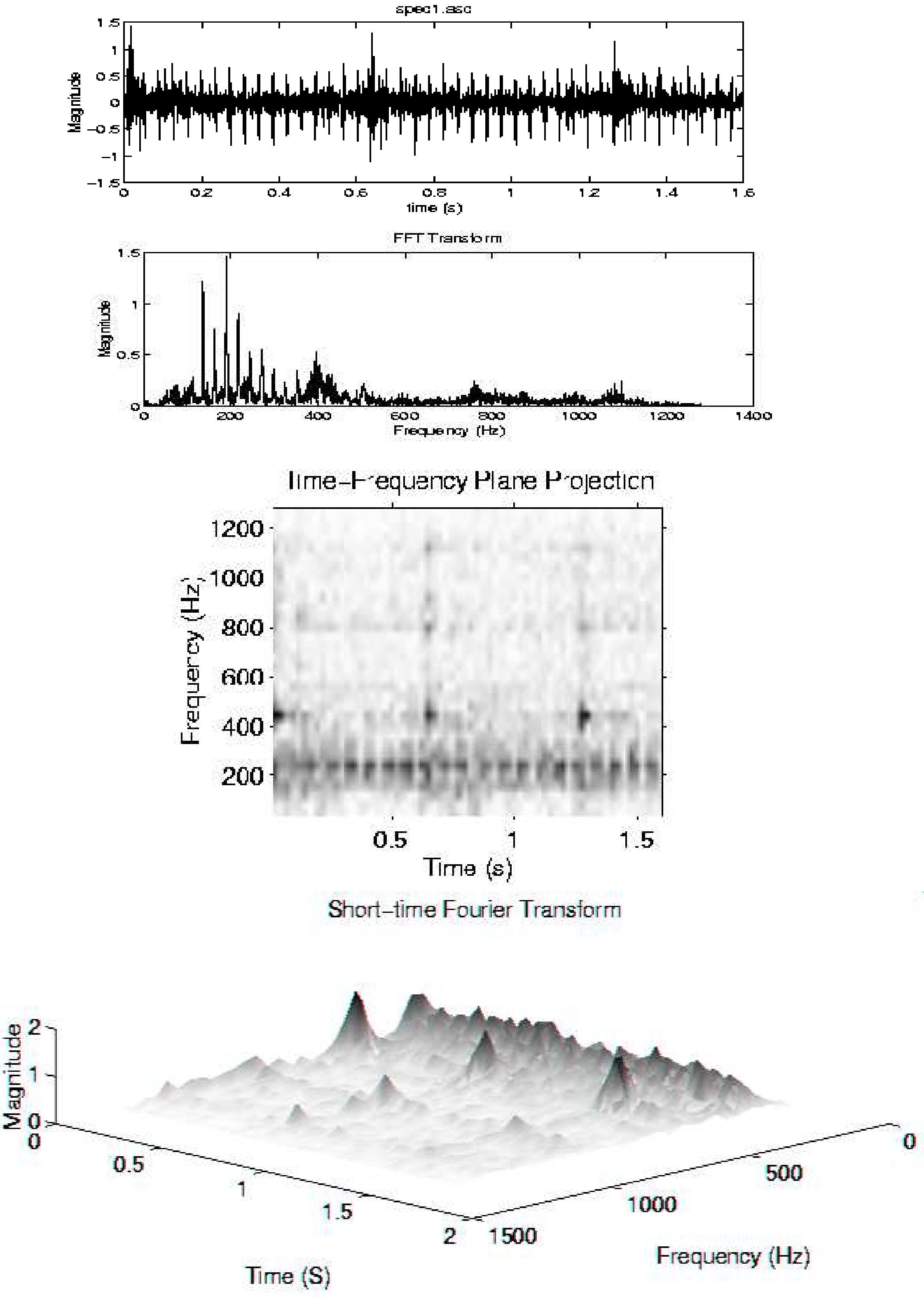

Figure 1: The signal measured on a defective gearbox, its spectrum and its short-time Fourier transform.