FAULT DIAGNOSIS IN BELT TRANSMISSION USING WAVELET ENVELOPED SPECTRUM

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Abstract: - In the recent years, there is a need for the evolution of methodologies for vibrational analysis by condition monitoring. In this regard, wavelet analysis has become a tool to efficiently detect the features of any vibration signal. The application of wavelet analysis for finding fault in the belt drive is presented in this paper. Vibration signal has been obtained from a healthy and faulty belt drive using a belt drive testing apparatus for experimental studies. The fault diagnostic capability of wavelet analysis has been compared by processing an experimental data. The experiment is done for various working conditions of belt drive. The advantages of wavelet analysis is shown in comparison with Fast Fourier Transform.

Keywords: Fault Diagnosis, Vibration signature; Fast Fourier transform; Continuous wavelet transform; Vibration Measuring Techniques; Envelope power spectrum; Wavelet;

1. Introduction
The machines have made the life easy. It has become the most important part of any activity. Machines reduces the effort that is required to achieve any task. It is very important to have good longevity for the machines. It can be achieved by regular maintenance. The regular maintenance also gives reliability and safety. The maintenance period depends on the behaviour and health of the machine. Scientists are trying to maximize the machine work. The condition monitoring is the technique, which helps to make the machine to work for maximum time by predicting its time of failure. There are many techniques in condition monitoring. Vibrations monitoring is one of them. It analyses the running condition of the machine and identifies the faults in it. The belt conveyors are used mainly in coalmines. It consists of many idlers. The daily production of the industry is affected by the faults in belt conveyors. Diagnosis methods are used to determine the faults in the idlers. The belt drive test setup is used for experimental investigation and the report is presented in this paper.

2. Literature review
The machineries in the industries may develop fault in various parts and these faults reduces the productivity and increases the maintenance cost. The production can be increased and the maintenance cost can be decreased by using the predictive maintenance technique. The malfunctioning and breakage of the system during operation can be reduced by developing a suitable condition monitoring technique. Early detection of fault can help in avoiding serious damage to the complete system. The vibration based condition monitoring techniques are broadly used in many mechanical components like gears, bearings [1], [2]. There are different techniques like time; frequency and time-frequency domain used in the analysis of vibration signal [3], [4], [5]. The statistical characteristics such as impulse factor, shape factor, crest factor, standard deviation, peak level, Kurtosis are used in the time domain techniques. Fast Fourier Transform of time domain, cepstrum, power spectrum etc. is used in frequency domain techniques. These techniques assume that there is a stationary signal of vibration. The FFT is used in analyzing harmonic signals because it represents a signal with finite time duration.
It is poor in analyzing transient signal components since it has a constant time and frequency resolution [6]. The non-stationary signal are produced due to the fault. The information about the machine faults can be obtained from these non-stationary components. Hence, non-stationary signal needs to be analyzed. The time frequency technique helps in the time evolution of frequency content [7], [8]. The non-stationary signals can be analyzed by using new time variant techniques. The energy distribution in can be described by the time and frequency distribution. The STFT can be used to produce the energy density spectrum known as spectrogram. The fast variations obtained from narrow time windows results in poor resolution of frequency. Analysis of the signal becomes complicated while using signal with low and high frequency components [3]. The WVD can provide better resolution as compared to the STFT. The main deficiency of the WVD is cross term interference [3], [9]. The transient signal characteristic features of non-stationary vibration signals produced by the faults can be extracted by the wavelet transform (WT) in time and frequency domain. The wavelet analysis includes the identification of similarity in the wavelet base function. The fault related features are extracted by analyzing the wavelet coefficients. There are many wavelet-based functions with high sensitivity for the mechanical fault detection. The fault features in rolling elements, such as ball bearing and gear are extracted by using Morlet wavelet and Impulse wavelet. The fault detection process is then enhanced by optimizing the wavelet parameters based on maximum Kurtosis. [14], [15]. It is also used for the diagnosis of intake valve of an internal combustion engine [17]. At present there is no online condition monitoring system. The Morlet wavelet is not flexible in signal analysis, but it provides smoothing. The Haar wavelet does not provide smoothing, but it is very easy to implement.

3. Experimental details

3.1 Continuous Wavelet Transfer

The enlarged or compressed versions of the basic function and translation are a family. A continuous wavelet transform is given by the equation (1) as follows.

$$W(a, b) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{|a|}} \Psi \ast \left( \frac{t-b}{a} \right) dt$$

Where, x(t) is the finite energy signal, Ψ is the analyzing signal and ‘b’ is the dilation parameter. The wavelet function Ψ is stretched, when the value of ‘a’ is greater than one. For the value of ‘a’ less than one, the function Ψ is contracted along the time axis. The negative value of ‘a’ flips the probing function on the time axis [22]. The value of wavelet function Ψ is in the oscillatory form. Hence, it is called as wavelet. When the value b = 0 and a = 1, the base wavelet is generated. This is the natural form of the wavelet and it is termed as mother wavelet. At a given combination of scale and position ‘a, b’, the similarity between the waveform and the wavelet are given by the wavelet coefficients W(a, b). In wavelet analysis, a most clear approximation of the shape of the wavelet is searched over the waveform. The search may be carried out over a range of wavelet sizes. The shape of the wavelet remains the same, but the time span varies. The wavelet is designed to have net area as zero. If the wavelet has constant waveform throughout its length, then it gives zero coefficients. When the wavelet coefficients have same scale as the wavelet, they respond more strongly. However, when the wavelet coefficients resemble the wavelet, they respond most strongly.

3.2 Enveloped wavelet power spectrum

The modulating signal can be extracted from an amplitude-modulated signal by the envelope detection or amplitude demodulation technique. Hence, the time history of the modulating signal is obtained. The modulating signal has envelope analysis as the FFT frequency spectrum. The vibration signal obtained from a faulty machine part may be considered as a carrier signal. This signal has a resonant frequency of that part, which is modulated by a decaying envelope. The oscillation caused by the impact needs to be replaced with a single pulse over the complete period of the impact.

The Morlet wavelet is given by the following equation.

$$\Psi(t) = e^{-t^2} \cos \left( \frac{\pi}{\sqrt{ln^2}} t \right)$$

$$e^{-t^2} \cos \left( \frac{\pi}{\sqrt{ln^2}} t \right)$$

$$-----(2)$$
Where \( x(t) \) is the finite energy signal, \( \Psi(t) \) is the mother wavelet and \( \Psi^{*}_{ab} \) is the scaled and conjugate wavelet. For calculating the wavelet transform, both real and complex wavelet are employed. Hence, the result of the wavelet transform is also an analytical signal. This is shown in equation (3) and (4).

\[
\text{WT}\{x(t),a,b\} \leq x(t), \quad \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \Psi^{*}_{ab}(t) dt \\
\text{Re}\{\text{WT}(a,b)\} + \text{Im}\{\text{WT}(a,b)\} = A(a,b) e^{i\theta(a,b)}
\]

Where \( \Psi_{a,b} \) is the family of daughter wavelet. It is defined by the dilation parameter ‘a’ and translation parameter b. The factor \( 1/\sqrt{a} \) ensures the energy preservation \( A(a,b) \) is the instantaneous envelope of the resulting wavelet transform (EWT). It extracts the slow time variation of the signal. It is given by the following equation.

\[
A(a,b)=\text{EWT}(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \Psi^{*}_{ab}(t) dt
\]

3.3 Experimental Setup and Procedure

The vibration data is collected from the experimental setup, which is designed and fabricated as per the requirements as shown in figure 1. The driver pulley is connected to a motor of 0.5hp power. The power rating capacity is 0.37kW. Bearings are used to support shaft. Pulleys are used for mounting the belts. The outer diameter of larger pulley is 100mm. The outer diameter of smaller pulley is 50mm. Two pulleys are mounted on the motor and two pulleys are mounted on the shaft. The driver and driven pulleys are connected by a V-Belt. The entire setup is mounted on a robust wooden platform.

![Figure1. Belt Drive Experimental Setup](image)

Accelerometer (Model 621B40, IMI sensors, sensitivity is 1.02 mV/m/s2 and frequency range up to 18 kHz) is used for collecting the vibration data from the belt drive by using NI Data Acquisition Device.

| Stage | Condition of the Belt | Fault description |
|-------|-----------------------|-------------------|
| Stage 0 | Healthy Belt | No fault is induced. |
| Stage 1 | Faulty Belt | 5mm side cut in |
| Stage 2 | Faulty Belt | 2mm side cut out |
| Stage 3 | Faulty Belt | 2mm loose |

Healthy condition: The experiment was conducted for a speed of driver pulley at 1451 RPM and 755RPM. The speed is measured by tachometer. The vibration signals are collected in three axes using
LabView7.1 software. The signals collected in healthy condition of the system are used for comparing the signals at faulty condition.

Faulty condition: The belt was induced with three kinds of faults for the study and analysis under different speeds. One fault was induced at inner surface of the belt and is known as Side-Cut-In. The second fault was induced at the outer periphery of the belt and is known as Side-Cut-Out fault. The third fault is loose fault, which is induced at the outer side of the belt with slight loose condition.

Belt frequency calculation
The Belt speed can be obtained by the formula,

\[ \text{Belt speed} = \frac{\pi \times PS \times PD}{BL} \]  

Where PS = Pulley speed = 1451RPM and 755RPM
PD = Pulley diameter = 0.1m
BL = Belt Length = 36inch = 0.9144m
The higher speed of belt is 498RPM. The belt frequency is 8.3Hz.
The lower speed of belt is 259RPM. The belt frequency is 4.3Hz.

3.4 Wavelet Power Spectrum Implementation
The localized fault in the belt drive is detected by using several applications that helps to visualize the performance of the proposed approach. The fault condition is indicated by the increment in the number and amplitude of sidebands. The three dimensional accelerometer is used for obtaining the time domain signal from the experimental setup. The signal hence obtained is processed using various signal-processing techniques.

Figure 2: Methodology of envelope power spectrum implementation

4. Results and Discussions
A. FFT Power spectrum for high speed in X direction
The above figure 3 shows the FFT Power spectrum, which helps to identify the fault in the belt by comparing the vibration signal with the healthy condition. The FFT power spectrum gives a poor reading of the amplitude and it cannot recognize the small amplitude.

**B. Morlet Wavelet Based Enveloped Power Spectrum for high speed in X direction**

![Figure 3: FFT Power spectrum for high speed in X direction. (a) Healthy, (b) Side cut in, (c) Side cut out, (d) Loose condition.](image-url)
Figure 4: Morlet Wavelet Based Enveloped Power spectrum. (a) Healthy, (b) Side cut in, (c) Side cut out, (d) Loose condition

Figure 4 shows Morlet Wavelet Based Enveloped Power spectrum for healthy and faulty belt conditions. The Morlet Wavelet Based Enveloped Power Spectrum gives a better reading of the vibration amplitude and hence helps to compare the faulty condition with the healthy condition.

Figure 5: Comparison of amplitude of belt frequency for different belt conditions.
The above figure 5 shows the comparison of amplitude of vibration under different faults in the belt. The amplitude was minimum for the healthy condition. The amplitude increases while inducing fault in it. The loose belt was found to be having maximum vibration.

C. FFT Power spectrum for low speed in X direction

The above figure 6 shows the FFT Power spectrum. It can be used to identify the fault in the belt by comparing the vibration signal with the healthy condition. The amplitude of vibration was found low at lower speed.

**Figure 6**: FFT Power spectrum for low speed in X direction. (a) Healthy, (b) Side cut in, (c) Side cut out, (d) Loose condition.
D. Morlet Wavelet Based Enveloped Power Spectrum for low speed in X direction

Figure 7: Morlet Wavelet Based Enveloped Power spectrum for low speed in X direction. (a) Healthy, (b) Side cut in, (c) Side cut out, (d) Loose condition

Figure 7 shows Morlet Wavelet Based Enveloped Power spectrum for healthy and faulty belt conditions at low speed. The Morlet Wavelet Based Enveloped Power Spectrum gives a better reading of the vibration amplitude and hence helps to compare the faulty condition with the healthy condition.
Figure 8: Comparison of amplitude of belt frequency for different belt speed.

In the above figure 8, a comparison has been made for 2 different speed of the belt. The amplitude of the belt was small for the lower belt speed and it increases with increase in the belt speed.

Figure 9: Comparison of amplitude of belt frequency measured in X, Y, Z directions.

The amplitude of vibration, which is directly proportional to the degree of fault, also depends on the direction of measurement. The experiment shows that the horizontal X direction and vertical Y direction gives better reading of the vibration as compared to the axial Z direction.

5. Conclusions
The vibration signal is processed by using signal-processing techniques, such as Fast Fourier Transform and Morlet wavelet enveloped power spectrum. The results are compared for three different faults induced in the belt. The result shows that the Morlet wavelet enveloped power spectrum is more sensitive to the fault as compared to the Fast Fourier Transform. The amplitude of the vibration was found to be maximum for the loose condition. The vibration level was less during the low speed of the belt. The vibration level increases with increase in the belt speed. The vibration signals were recorded in all the 3 directions and the quality of the signal was found to be good in the horizontal and vertical directions.

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