A Review on Vibration Analysis for Misalignment of Shaft in Rotary Systems by Using Discrete Wavelet Transform

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Abstract— *During the assembly of machines the rotary shafts are aligned properly within the given specified tolerance limit. One of the major problem with rotating shaft is misalignment. Present technique available to find out the misalignment in rotating shaft is FFT (Fast Fourier Transform) analyzer. However an important deficiency of the FFT that it is not an effective tool to analyze non-stationary signals, so we lose the time information when a particular event took place. Then the Short-Time Fourier Transform is a modified version of the fourier transform invented to analyze the non-stationary signals. In STFT, the signal is separated into small enough segments, where these segments of the signal can be assumed to be stationary. The main drawback of STFT is that once a particular size time window is chosen, then the window remains same for all the frequencies. For vibration analysis of mechanical faults, presently the WT (Wavelet Transform) is developed as an alternative approach to the STFT to overcome the resolution problem. The DWT (Discrete Wavelet Transform) provides a time-frequency representation of signal. It allows the use of long time intervals where low-frequency information is desired and also takes shorter time intervals where high- frequency information is desired.*

Keywords— Misalignment in rotating shaft, FFT (Fast Fourier Transform), non-stationary signals, STFT (Short-Time Fourier Transform), WT (Wavelet Transform), DWT (Discrete Wavelet Transform), time-frequency representation

1. INTRODUCTION

In mechanical engineering, rotor systems have been widely used. Misalignment is one of the most common difficulties in the operation of rotating machinery. Any defect in machine will affect vibration behavior and nature of this effect is different for different faults. Vibration signals give early indication of mechanical failures such as misalignment, unbalance, crack and bent shaft etc. The presence of shaft misalignment can greatly influence on vibration response of machinery. However, it's detection through vibration analysis is not a straightforward due to the variability in vibration responses even when identical alignment exists.

Misalignment is categorized into three types,
(1) Parallel Misalignment, (2) Angular Misalignment and (3) Combined Misalignment as shown in fig. 1.1

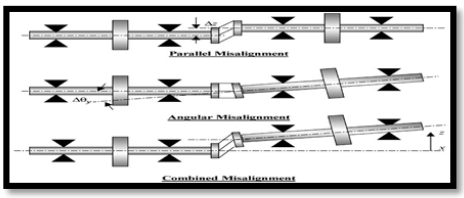

Fig. 1.1 Schematic of rotor with misalignment at a coupling [8]

For parallel misalignment, the center lines of both shafts are parallel but they are offset from each other. While for angular misalignment, the shafts are at an angle to each other.

Vibration response for misalignment shows up in the frequency domain as a series of harmonics of the running speed. The harmonics occurs because of the strain introduced in the shaft.

Xu and Marangoni [1] represents theoretical model of motor-flexible coupling which behaves like exactly as a universal joint to take the misalignment effects into account. He also derived the misalignment forces based on kinematics of Hooke's joint. They indicate the forcing frequency due to shaft misalignment are even multiple frequencies of the motor rotational speed.

Dwell and Mitchell [2] developed that expected vibration frequency for a misaligned metallic disk flexible coupling. The pre-dominant frequency were 2X and 4X running speed components shown due to misalignment increases.

Sekhar and Prabhu [3] proposed vibration responses for misaligned system by considering theoretical model of rotor bearing system. It consists of flexible diaphragm coupling at center of shaft, four bearings (two bearings at the end and two bearings near coupling), two rotors of same size and weight at center distance between coupling and within the two bearings (one at end and another at near coupling). They got 1X response with unbalance without misalignment and also they achieve 2X response with unbalance and misalignment. The coupling misalignment forces and moments have been determined for both parallel and angular misalignment. They concluded that the increase in harmonics with misalignment can easily be calculated by using FEM analysis.

K. M. Al-Hussain and I. Redmond [4] published paper by consisting model of rigid coupling at center of shaft, four bearings (two bearings at the end and two bearings near coupling), two rotors of same size and weight at center distance between coupling and within the two bearings (one at end and another at near coupling). The model was to be made in such a way that by considering lateral and torsional vibrations of two rotors subjected to pure parallel misalignment. They developed mathematical modelling for proposed system by Lagrange's equation. The steady state spectra reveals that the 1X running speed component was present in the vibration response. This study does not provide any evidence for the presence of second or higher order harmonics represents which a characteristic of normally observed in misalignment of shaft. They also suggest that the modelling of misaligned coupling using kinematics of Hooke's joint is not suitable for all types of flexible couplings as orthogonality between driver and driven hub rotation vector is not possible for other types of coupling.

A.W. Lees [5] studied the effect of parallel misalignment in rigidly coupled rotors. He was proposed that kinematics of the connecting bolts of a 3 pin coupling. He concluded that getting 2X vibration response due to presence of misalignment.

Tejas H. Patel and Ashish K. Dharpe [6] published a paper in which they studied effects of parallel and angular misalignment on the vibration behavior of the coupled rotors. For experimental setup they considered two rotors of different sizes and weight supported on rolling element bearings. In this setup they used a pin-bush (three-pin) type flexible coupling. They found that the misalignment couples vibrations in bending, longitudinal and torsional modes. Some diagnostic features in the FFT of torsional and longitudinal response related to parallel and angular misalignment have been shown. They concluded that for parallel misalignment 1X vibration response is stronger in axial-torsional vibration than lateral-axial vibration. Similarly for angular misalignment 3X vibration response is stronger in axial-torsional vibration.

P. N. Savedra and D. E. Ramirez [7] calculated vibration spectra for two flexible couplings: a three-pin Reynold coupling and a three-jaw Lovejoy coupling. They consider theoretical model for two times by consisting of coupling (one time three-pin Reynold coupling and another time three-jaw Lovejoy coupling) at center of shaft, four bearings (two bearings at the end and two bearings near coupling), two rotors of different size and different weight at center distance between coupling and within the two bearings (one at end and another at near coupling). They concluded that for misalignment with a three-pin Reynold coupling got 1X vibration response while with a three-pin Reynold coupling got 3X vibration response.

Now a day's wavelet transform is used for mechanical faults detection due to its time-frequency representation better than FFT.

ABBREVIATION

Symbol	***Description***
FT	Fourier Transform
FFT	Fast Fourier Transform
STFT	Short Time Fourier Transform
WT	Wavelet Transform
CWT	Continuous Wavelet Transform
DWT	Discrete Wavelet Transform
WPT	Wavelet Packet Transform
EMD	Empirical Mode Decomposition
WVD	Wigner's Ville Distribution
HHT	Hilbert Huang Transform

2. VARIOUS VIBRATION ANALYSIS TECHNIQUES

Following are the various techniques used for the vibration analysis techniques.

A. Fourier based approach

B. Wavelet transform based approach

A. Fourier-Based Approach to Vibrational Analysis

Traditional vibration signal analysis has generally relied upon spectrum analysis via the Fourier Transform (FT).

A.1. Fast Fourier Transform (FFT)

The FFT represents a time waveform into its sinusoidal components. FFT takes a block of time-domain data and coverts it into the frequency spectrum of the data.

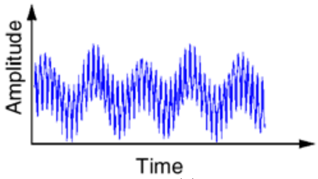

Fig. 2.1 (a)

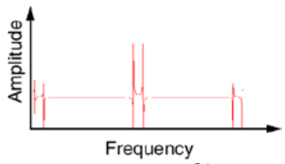

Fig. 2.1 (b)

Fig. 2.1 Transfers signal f(t) from a time-based to a frequency based domain

Based on spectral approaches such as the FFT are influential in diagnosing a variety of vibration related problem in rotating machinery. Fourier analysis transfers a signal f(t) from a time-based domain as shown in fig. 2.1 (a) to a frequency based one as shown in fig. 2.1 (b), thus generating the spectrum F(ω) that includes all of the signal's constituent frequencies and which is defined as

$$F(\omega) = \int_{-\infty}^{\infty} f(t).e^{-i\omega t}.dt \quad [11] \qquad (1)$$

Where, ω = frequency

f (t) = Time function

A.1.1 Problem with FFT

An important deficiency of the FFT that it is unable to provide any information about the time dependence of the spectrum of the signal examined, so results are averaged over the entire interval of the signal i.e. by using FFT, we miss the time information when a particular event took place.

A.2 Short-Time Fourier Transformation (STFT)

The STFT is a modified version of the fourier transform. The FT separates the input signal into a sum of sinusoids of different frequencies and also identifies their respective amplitudes. Thus, the FT gives the frequency-amplitude representation of input signal. The FT is not an effective tool to analyze non-stationary Signals. STFT and WT are helpful tools to analyses non-stationary signals.

In STFT, the non-stationary signal is separated into small portions, which are assumed to be stationary. This is done using a window function of a chosen width, which is shifted and multiplied with the signal to obtain small stationary signals. In STFT, the signal is divided into small enough segments, where these segments (portions) of the signal can be assumed to be stationary.

A.2.1 Drawback of STFT

The main drawback of STFT is that once a particular size time window is chosen, the window remains the same for all frequencies.

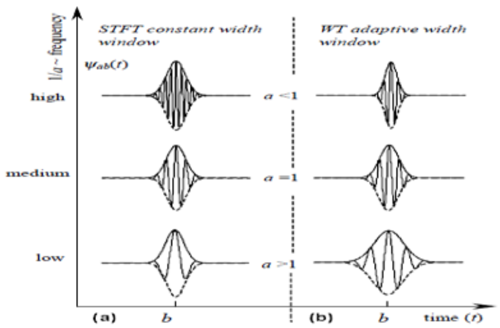

Fig. 2.2 Varying the scale parameter *a* in the case of the short time Fourier transform (a); and the wavelet transform (b) [15]

Fig. 2.2 (a) shows varying the scale parameter *a* in the case of the short time Fourier transform while Fig. 2.2 (b) shows varying the scale parameter *a* in the case of the wavelet transform.

To analyze the signal effectively, a more flexible approach is needed where the window size can vary in order to determine more accurately either the time or frequency information of the signal. This problem is known as the resolution problem.

B. Wavelet Transform (WT) Based Approach

A wave is an oscillating function of time or space that is periodic. The wave is an infinite length continuous function in time or space. In contrast, wavelets are localized waves. A wavelet is a waveform of an effectively limited duration that has an average value of zero.

WT is process of correlation shifting & scaling of signal with the small duration wavelet. WT theory is one of the most promising signal processing tools for vibration analysis and now is widely used for damage detection in machine components.

The WT provides a time-frequency representation of signal. The WT was developed to overcome the shortcomings of the STFT, which can be used to analyses non-stationary signals. The WT is generally termed mathematical microscope in which big wavelets give an approximate image of the signal, while the smaller wavelets zoom in on the small details.

The basic idea of the WT is to represent the signal to be analyzed as a superposition of wavelets. It allows the use of long time intervals where more precise low-frequency information is desired and also permits the use of shorter time intervals where accurate high-frequency information is desired.

B.1 Continuous Wavelet Transform (CWT)

The CWT was developed as an alternative method to the STFT for overcome the resolution problem.

The wavelet analysis is done in a similar way to the STFT analysis, in the sense that the signal is multiplied with a function wavelet similar to the window function in the STFT, and the transform is computed separately for different segments of the time domain signal.

Thus the continuous wavelet transform (CWT) gives excellent time-frequency characteristics. In order to analyze signals of very different sizes, it is necessary to use time-frequency atoms with different time supports. The wavelet transform decomposes signals over dilated and translated functions called wavelets, which transform a continuous function into a highly redundant function.

The CWT of a signal x(t) is given by

$$w_x(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}\varphi^*\left(\frac{t-b}{a}\right)x(t)\,dt \quad [15] \qquad (2)$$

The CWT is a function of two variables a and b.

Here a = scaling factor

b=shifting parameter

$\varphi(t)$ = mother wavelet or the basis function which is used for generating all the basis functions.

$\frac{1}{\sqrt{a}}$ = factor included for energy normalization.

The mother wavelet is translated and dilated into the daughter wavelet $\psi_{ab}(t)$ as

$$\psi_{ab}(t)=\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \quad [15] \qquad (3)$$

Where, $\psi\left(\frac{t-b}{a}\right)$ = The mother wavelet translated by a factor of *b* and dilated by *a*.

$\psi_{ab}(t)$ = The daughter wavelet changes continuously due to varying the scaling parameter and changing a and b.

The translation parameter or the shifting parameter ‘b’ gives the time information in WT. It indicates the location of window as it is shifted through the signal. The scale parameter ‘a’ gives the frequency information in the WT. A low scale corresponds to wavelets of larger width which gives the global view of the signal.

B.2 Discrete Wavelet Transform (DWT)

The Discrete wavelet transform (DWT) is obtained by filtering the signal through a series of digital filters at different scales. The scaling operation is done by changing the resolution of the signal by process of subsampling.

The DWT can be computed using either convolution-based or lifting-based procedures. In both methods, the input sequence is decomposed into low-pass and high-pass sub-bands, each of half the number of samples in the original sequence.

Wavelet transform is process of correlation translating and dilating of the signal with the small duration wavelet. DWT is discrete in terms of sampling translating and dilating parameters not in terms of signal. A DWT permit systematic decomposition of signal into its frequency sub-band with minimum distortion of signal, this process is achieved by using two channel sub band coder proposed by Mallat in 1989, in which low frequency and is referred as approximate and high frequency band is referred as detail wavelet analysis splits-up the signal into shifted and scaled version of function called mother wavelet, DWT uses filter bank of low pass and high pass filter which is followed by down sampling to compute approximate and detail coefficient where approximate is low pass filtered and detail is high pass filter which is derived from mother wavelet.

The process is continue with the approximate (low frequency) coefficient to increase the level of decomposition by further breaking it up in approximate and detail part as shown in the Figure 2.3. The shape and the frequency response of these filter depends on the type and order of mother wavelet used in analysis.

In DWT, the two parameters *a* and *b* which are for scaling and translating, respectively can be defined as functions of level *j* and position *k*

$a=2^{-j} \quad j\in Z,\ b=a,k \qquad k=0\ldots..n-1$ [15] (4)

Then the analyzing function y becomes,

$$\psi_{j,k}= 2^{j/2}\,\psi(2^{j}\,t-k) \qquad [15] \qquad (5)$$

Where (t) is called mother wavelet
and $\psi_{j,k}$ called Discrete daughter wavelet.

Here the level j determines how many wavelets are needed to cover the mother wavelet, and the number k determines the position of the wavelet and gives the indication of time.

It is possible to decompose any arbitrary signal x(t) into its wavelet components.

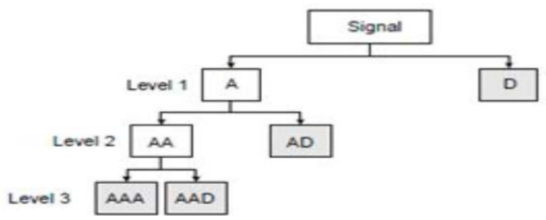

Fig. 2.3 DWT Decomposition at level 3 [12]

C. Comparison of Analysis Techniques Based on Computation Time

Furthermore there are some other analyses techniques are available for diagnosis of faults present in the rotating machine they are

- Wavelet Packet Transform (WPT)
- Empirical Mode Decomposition (EMD)
- Wigner's Ville Distribution (WVD)
- Hilbert Huang Transform (HHT)

Each technique has its own advantages and limitation in which the computation time plays important role in the real time diagnosis of the fault. A comparison of the all the signal processing technique based on their computations time required for analysis of the signal is demonstrated using the bar chart in the Figure 2.4.

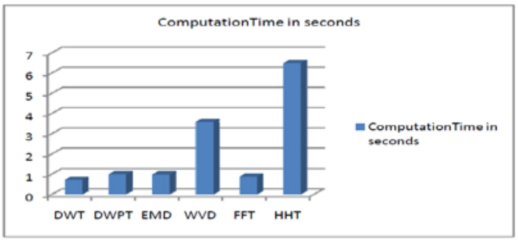

Fig 2.4 Computation time of the various signal processing techniques [12]

A suitability of the various signal processing techniques are verified in terms of their computation effort Figure. 2.4 illustrate and compare the computational effort of different signal processing in which the highest computational effort is observed in the HHT whereas the lowest is in the DWT, by this DWT can be selected as the most suitable signal processing with lowest computation effort.

3. PROPOSED EXPERIMENTAL SETUP

Due to misalignment, high stresses and high vibration occurs in the rotating system. Hence it is very important to detect the misalignment of rotating shaft to reduce excessive vibration, noise, less production rate etc.

Misalignment is categorized in three types, (1) Parallel Misalignment, (2) Angular Misalignment and (3) Combined Misalignment

Presently the advanced technique WT (Wavelet Transform) is one of the most promising signal processing tools for vibration analysis and now is widely used for damage detection in machine components. The DWT (Discrete Wavelet Transform) was developed as an alternative approach to the STFT to overcome the resolution problem. The DWT is obtained by filtering the signal through a series of digital filters at different scales. The DWT provides a time-frequency representation of signal. It allows the use of long time intervals where more precise low-frequency information is desired and also permits the use of shorter time intervals where accurate high- frequency information is desired.

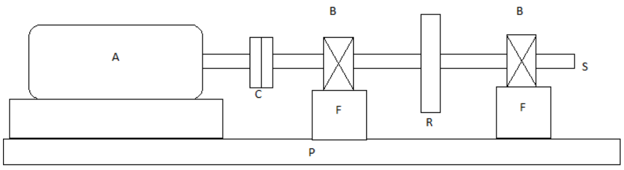

Fig.3.1 Schematic diagram for experimental setup

Nomenclature for fig. 3.1 is as follows A- Motor, B- Bearings, C- Coupling, R- Rotor, F- Bearing Supports, S- Shaft, P- Base Plate.

In this work make a setup which consists of base plate, induction motor, shaft, coupling, two bearings, two fixtures for bearing supports, one rotor located in between two bearings as shown in fig. 3.1.

For checking misalignment use dial gauges, also for controlling speed of motor use variable frequency drive.

In this work, DWT technique will used to find out the vibration response of the misalignment of rotating shafts to overcome the problems of FFT.

4. SUMMARY

From literature survey it is summarized as follows

- For detection of misalignment in rotary system the vibration response can be characterized primarily two times shaft running speed (2X) by using FFT analyzer.
- The Discrete wavelet transform (DWT) is developed as an alternative approach to detect mechanical faults in rotary systems by resolving problem of STFT.
- DWT analysis technique give good pictorial representation of the changing faults in system with less computation time than FFT.
- DWT presents relative changes in amplitude very clearly this feature is not present in other signal processing techniques that are not localized in time and frequency.
- From this setup also 2X vibration response will expected for misalignment in rotary shaft with DWT.

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