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A Review on Gear Fault Analysis

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ABSTRACT: A vibration analysis is about the art of looking for changes in the vibration pattern, and then relating those changes back to the machines mechanical design. The level of vibration and the pattern of the vibration tell us some-thing about the internal condition of the rotating component. The vibration pattern can tell us if the machine is out of balance or out of alignment. Al-so faults with the rolling elements and coupling problems can be detected. This paper presents a review of gear faults presents in the gear, and methods to check it.

KEYWORDS: Gear Fault, IMD, EMF

I. INTRODUCTION

Maintenance can be described as fixing or replacing something that is broken. Also is defined as performing routine actions in order to keep a machine running or preventing any further problem.
Maintenance includes:

- Operation: Process control, use of machines, small component changes
- Keeping machine running: Cleaning, lubrication, monitoring
- Logistics: Selection, procurement and delivery of resources
- Improvement: Without changing the object's original action
- Changes: Changes to the original function
- Factory service: e.g. security, fire protection, sanitation, waste- and snow removal .

Why do we perform maintenance services? “Failure” is the answer. When a machine does not perform a required function as a result of an incident, this can be described as a failure. In most of the cases failures can be anticipated through a good maintenance plan, but the possibility of unpredictable critical failures is always present.

1.2.1 Common reasons for failures:

- Equipment is not used in the right way
- Too much focus on repairing instead of checking and analyzing
- The operating conditions are not optimal
- The design does not adequately take into account the actual use or the conditions of use.

Equipment operators detect symptomatic defects, but they don’t take any action or reports.

1.3 Importance of vibration analysis

Vibration measurements give us the information needed to understand why problems have occurred. If we can interpret the data obtained in a correct way and perhaps change the way a machine is operated or maintained, the machine will become more reliable in the future making the overall process more profitable.

Therefore by including vibration measurements into our maintenance plan we can save money and in most of the cases improve the product quality.

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1.4 Vibration in a Rotating Machine

Rotating machines are the most common type of machines found in different industry fields and they have to work with high performances. An unscheduled stop due to the machine's failure leads to high maintenance and production costs risks. High costs are initiated through the production stops, losses, and urgent procurements of spare parts. High risks are associated with the possibilities of workers' injuries and secondary damages of neighboring machines. To avoid such a scenario, several maintenance strategies have been developed, from the breakdown maintenance to condition based and proactive maintenance. The implementation of condition-based maintenance implies monitoring of machine operating condition based on the physical parameter that is sensitive to machine degradation. Among many possible parameters, mechanical vibration acquired at the bearing's housing is one of the best parameter for early detection of a developing fault inside a machine. Methods of vibration signal analysis enable the extraction of type and severity of a fault. Despite the fact that the information on type and severity of a fault is contained in the vibration signal, due to the:

- ***a) Existence of multiple faults on a machine,***
- ***b) Dependence of vibration signal content on operating conditions,***
- c) ***Existence of vibration components from neighboring machines***,

Derivation of incorrect vibrodiagnostical conclusions and wrong estimation of machine criticality in the plant, is a very common situation.

To avoid this, there are two approaches:

- ***a. Engagement of highly skilled and trained vibration analysts or***
- ***b. Application of artificial intelligence (AI) methods for reliable extraction of an existing fault.***

Engagement of certified vibration analysts can be a problematic issue due to the following reasons: there are not many of them, in many cases they don't have a substitution when absent and they are often engaged in other maintenance tasks so they cannot be fully focused on the analysis of acquired data from the machine. In such an environment, implementation of AI methods through previously developed and validated fault identification algorithm has a huge potential.

The monitoring of a Gearbox condition is a vital activity because of its importance in power transmission in any industry. Techniques such as wear and debris analysis, and acoustic emissions require accessibility to the Gearbox either to collect samples or to mount the transducers on or near the Gearbox. Vibration analysis is one of the most important condition monitoring technique that are applied in real life. Most of the defects encountered in the rotating machinery give rise to a distinct vibration pattern (vibration signature) and hence mostly faults can be identified using vibration signature analysis techniques. Vibration Monitoring is the ability to record and identify vibration "Signatures" which makes the technique so powerful for monitoring rotating machinery.

II. Background and Literature Survey

Due to the industrial importance of gears in power transmission systems, the effective CM of gearboxes is essential. There is constant pressure to improve measuring techniques and tools for the early detection and diagnosis of gearbox faults. The gears themselves are the most important elements in the gearbox, and the degree of wear and fatigue to which they are subjected even under normal operating conditions means that they are often subject to premature failure. Ma and Li claim that up to two-thirds of gearbox failures are due to faults which develop in the gears, and almost all of these are due to localised defects such as fatigue induced fractures [1].

Increased demand for lower production and maintenance costs means that the CM of gear transmissions has become an important area of research. The severe conditions under which gears operate relative to other machine components, means that they deteriorate quite rapidly, especially their teeth [2]. Fakhfakh et al have defined three general types of gear defects that cause transmission error and gearbox failure:

- ***a. Manufacturing defects (e.g. error in the tooth profile),***
- ***b. Installation defects (e.g. the alignment of the gears)***
- ***c. Defects which occur during the work process (e.g. cracking of teeth) [2].***

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Sudden loading of the gear teeth during operation is the main factor causing fatigue cracks that appear at the root of the tooth and weaken the structural integrity of the gear.

Lin and Zuo have described tooth breakage as the most serious problem for gears because it can lead to complete failure of the gearbox [3]. Initially a fatigue crack at the base of a tooth will not be considered a serious problem, but as the crack propagates, damage will accelerate and may result in catastrophic tooth failure. If the crack can be detected and its development tracked, the gear can be replaced before the tooth breaks.

Much effort has gone into developing reliable methods for fault detection in gearboxes. Proven techniques include oil analysis [4], temperature distribution within the gearbox, the noise produced by the gearbox when in operation, motor current analysis [5] and, most popular today, vibration analysis [6]. Unfortunately, no single technique has been found that is able to detect all machine faults. Vibration measurement, which is the most widely used CM technique in industry, because of its proven ability to detect the early presence of faults, can identify only 60% to 70% of machine faults [7,8].

Vibration analysis is now usually performed online via a computer-based machine CM system and does not require shutdown of the machinery.

Analysis of vibration signals is very appropriate for monitoring gearboxes because any change in the vibration signature of the gearbox is most likely a result due a change in gearbox condition. This is because as defects on a gear will alter both the amplitude and phase modulations of the gear's vibrations. Thus, any changes in vibration signal can be analyzed to provide an indication of possible faults [9, 10]. Most natural phenomena are non-linear and the majority of these signals have varying frequency content. The vibrations of multi-stage gearboxes contain non-stationary transients, e.g. the short periodic impulsive components produced by impacts between components. Typically, vibration signals generated in gearboxes will contain three main components,

1. ***Periodic components such as those resulting from interactions between the gears during meshing,***
2. ***Transient components caused by short duration events, such as repeated impacts due to a tooth having broken off, and***
3. ***Broad-band background noise.***

In the early stages of damage and fault initiation, the resulting low amplitude vibration signal will be masked by other sources present in the gearbox and cannot therefore be used directly for damage detection. However, it is precisely at this stage that detection of these faults is important. As a result, more effective signal processing methods are required to better analyse vibration measurements and more reliable gearbox condition monitoring and health diagnosis.

Analysis of the time-domain signal uses statistical parameters such as peak value, root mean square (RMS), kurtosis and Crest factor (CF) and their use is well established in assessing the condition of gears [9]. Stevens et al have claimed that these measures are suitable for detection and diagnosis when mechanical faults take the form of impulses which impose periodic pulses of short time duration (wide frequency bandwidth) onto the base vibration signal [11].

However, the most common method used for detection and diagnosis of gear failure is spectral analysis of the vibration signal in the frequency-domain. This is because the most important CM elements in the vibration spectra of gears are: the tooth meshing frequency, harmonics and sidebands (due to modulation phenomena) located on either side of the gear tooth meshing frequency. The sidebands are separated by integer multiples of the gear rotation frequency. The behaviour of these sidebands can be strongly indicative of the presence of a fault, e.g., through an increase in the number of sidebands and their relative amplitudes. Randall found that the first three gear meshing harmonics and their sidebands provided sufficient information for gear fault identification [12].

Today, combined time and frequency analysis is increasingly used in gear fault diagnosis and is gradually replacing conventional time-domain analysis and frequency-domain analysis. Representing the signal in the time and frequency-domains simultaneously is a powerful tool for examining non-stationary vibration signals and the results can be easily interpreted. Wang and McFadden claim that it is relatively easy to characterise the local features of the signal, and all distinctive components in the frequency range of interest, their sequences causality and changes with time can be displayed on a single chart [14].

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During the past twenty years, a number of time-frequency signal processing techniques have proved to be suitable for analysis of vibration signals and have gained acceptance in the field of CM [15]; such approaches as the Short-Time Fourier Transform (STFT) [14], Wigner-Ville Distribution (WVD) [16] and Wavelet Transforms (WTs) [17, 18, 19] are widely used. Peng and Chu have claimed that the WT technique has proved eminently suitable for analysis of vibration signals because most signals contain instantaneous impulse trains and other elements which are transient and non-stationary in nature [19]. The WT decomposes a signal into different frequencies with different resolutions i.e. it provides time-scale (frequency) representation of a signal [18].

2.1 Time-domain Analysis

Time domain analysis of vibration signals is one of the simplest and cheapest fault detection approaches. Conventional time-domain analysis attempts to use the amplitude and temporal information contained in the gear vibration time signal to detect gear faults. The amplitude of the signal can be used to signal that a fault is present and the periodicity of the vibration can then indicate a likely source for the fault [11]. Time domain approaches are appropriate when periodic vibration is observed and faults produce wideband frequencies due to periodic impulses [11]. Use of the waveform enables changes in the vibration signature caused by faults to be detected, but it is difficult to diagnose the source of faults. Figure 2.1 (from section 4.2.1) shows the gearbox vibration waveform for healthy and faulty gear systems.

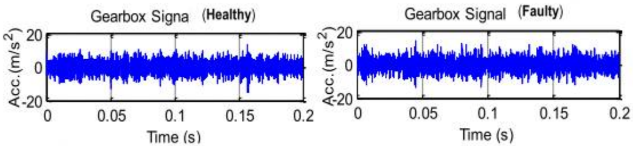

Figure 2.1-Waveform of the vibration signal for a gearbox with healthy and faulty gears

Some mechanical systems generate high vibration levels throughout their operation. When these systems develop a progressive fault, the resulting vibration level is likely to increase consistently with time but the increase in vibration may be very small and difficult to identify. If the rate of development of the fault vibration is small, it may not be possible to clearly determine a fault symptom from variations in the waveform of the signal [20].

Mechanical systems are termed deterministic if their properties such as displacement, acceleration, etc. can be predicted over time. Mechanical systems such as a gearbox with a localised fault reveal characteristics which cannot be estimated over time. The characteristics of such systems, termed random or non-deterministic, cannot be accurately predicted, but they can be estimated by statistical parameters and these parameters can be used to predict fault progression [21].

2.2 Frequency (Spectral) Domain Analysis

Frequency-domain analysis is a powerful conventional technique for vibration analysis and has been demonstrated as a useful tool for detection and diagnosis of faults in simple rotating machinery [22, 23]. Using this technique, the time-domain of the vibration signal is transformed into its frequency equivalent. It has been found that the spectral content of the measured signal is often much more useful than the time-domain for determining gear condition because the complex time-domain signal can be broken down into several frequency components. It is therefore easy for analysts to focus on these frequencies which are valuable in fault diagnosis [22], whereas the overall vibration is a measure of the vibration produced over a broadband of frequencies; the spectrum is a measure of the vibrations over a large number of discrete contiguous narrow frequency bands. Thus the common approach to vibration CM is use the Fast Fourier Transform (FFT) to transform the vibration signal to the frequency domain. This approach is perfectly acceptable if the measured signal does not vary in spectral content over time (i.e. no variations in the rotational speed of the machine).

For machines operating with known constant speed, the vibration frequencies of the vibrations produced by each component in the machine can be estimated therefore, any change in vibration level within a particular frequency band can be related to a particular component. Analysis of relative vibration levels at different frequency bands can provide some diagnostic information

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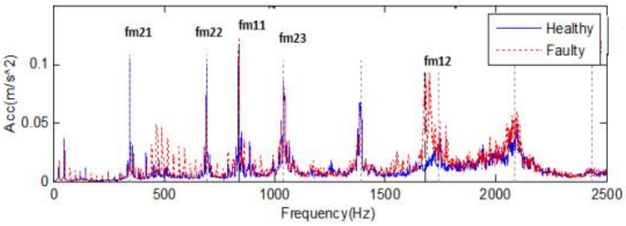

Figure 2.3-Spectrum of Gearbox Vibration Signal for Healthy (blue) and Faulty (red) gears

Sidebands generated by either amplitude modulation or frequency modulation of the vibration signal often provide useful information. Amplitude modulation is attributed to tooth fracture or eccentricity of the gear or shaft with a damaged tooth
generating pulses at a rate equal to the gear speed. Frequency modulation, on the other hand, is caused by errors generated during gear manufacture (e.g. non-uniform tooth spacing). As previously stated, Randall has claimed that the first three gear meshing harmonics and their sidebands provide sufficient information for the successful identification of gear faults [22].

Therefore, changes in the amplitude of a particular frequency peak or sidebands of a signal can provide a good indicator of potential gear failure. In practice, the spacing of the sidebands depends on periodic properties of the loading and on the transmission path, it can be difficult therefore to extract useful features directly from vibration spectra based solely on a FFT. When the signal to noise (S/N) is low and the vibration spectrum has a large number of frequency components due to the complexity of the system, it becomes almost impossible to distinguish the peaks due to faults from peaks from other sources. This is the most difficult problem associated with the FFT based fault detection approach.

2.3 Joint Time-Frequency Approaches

Analysis of the vibration signals in the time-domain and the frequency-domain produces signal characteristics for their respective domains only. The time-domain contains no spectral information and when a time-domain signal is transformed to the frequency-domain, the detailed information about the time-domain is lost.

It is often difficult to detect clear symptoms of any defect in the gear if Time Synchronous Averaging (TSA) is used in isolation [23]. The technique may also fail to detect and differentiate between faults, particularly if multiple faults are present simultaneously in multiple gears within the gearbox. A wide variety of different techniques have been explored over the years to further process the TSA method to make it more sensitive to early fault detection [24].

Recently, much work has been carried out on the analysis of vibration signals in the time-frequency domain, with a view to combining this with frequency domain analysis to give a full representation of a vibration signal [19].

The major differences between these transforms are their respective time and frequency resolutions. WT analysis has been shown as an ideal tool for condition monitoring of gears. In contrast to the STFT, the WT method uses narrow time windows at high frequencies and wide time windows at low frequencies [28, 29]. It is therefore a very effective method for the analysis of transient and non-stationary signals. Abnormal transients generated by early stage gear faults can be detected using discrete [9] and continuous [23] wavelet transformation. It has been found that even though the discrete WT offers a very efficient signal representation with no redundancies, the resulting time-scale map is limited, and not very informative. Lin et al. introduced a linear wavelet transform concept, whereby the wavelet map was normalized according to the signal amplitude instead of energy [3]. Boulahbal et al [30] applied both the WT amplitude and phase simultaneously to study cracked and chipped tooth faults and proposed polar representation as a useful tool for pinpointing the location of the gear damage in WT maps.

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2.4 Wavelet Transform

The Wavelet Transform method can be used as an alternative technique to the STFT. Where STFT is used to measure the local frequency content of the signal, the WT method compares several components of the vibration signal at different resolutions.

In recent years, several WT analyses have been accepted as suitable signal processing techniques for machine CM and failure diagnosis. By decomposing a time series into time-frequency space, it is possible to determine not only the existing frequencies in the signal but also the duration of each individual frequency in time [18, 19]. This is highly advantageous in examining vibration signals from faulty rotating machinery, where either large or small scale changes in the vibration may occur whether the fault is distributed or local [9]. When monitoring gearbox condition, WTs are used primarily to identify all possible transients in vibration signals which are generated by faults. WTs possess multiple resolutions for localization of short time components, enabling all possible types of gear fault to be displayed by a single time-scale distribution resulting from the transform [15].

III. CONCLUSION

This paper presents a study of various approaches for the analysis of faults presents in the gears. These approaches has been classified in to the categories; time domain analysis, frequency domain analysis, time-frequency domain analysis.

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