A VERSATILE AND COMPUTATIONALLY EFFICIENT
CONDITION INDICATOR FOR AH-64 ROTORCRAFT GEARBOXES

by

Praveen Kumar Nooli

Bachelor of Technology
Jawaharlal Nehru Technological University, 2005

Submitted in partial fulfillment of the Requirements
For the Degree of Master of Science in
Mechanical Engineering
College of Engineering & Information Technology
University of South Carolina
2011

Accepted by:
Abdel Bayoumi, Major Professor
Jeffrey Morehouse, Committee Member
Tim Mousseau, Dean of the Graduate School
DEDICATION

To my father, and mother who have sacrificed their life comforts and amusements for mine and my brother’s future. To my loving brother for alleviating my responsibilities and encouraging me to pursue the course I desired. You are the hallmarks of love, affection and sacrifice.
ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to my advisor, Professor Abdel E. Bayoumi for having inducting me into his research group and providing an opportunity to pursue independent research as I envisaged. His encouragement throughout my research and liberty in pursuing courses of my choice was invaluable. I would also like to thank my research sponsors, South Carolina Army National Guard (SCARNG), and my school, University of South Carolina. I owe many thanks to my mentor and friend, B S K Prasad for advising me all though my career and imbibing confidence in me. Special thanks to Rakesh Ponnala for helping me out and introducing me to many other friends here in Columbia. I also thank all my friends in Columbia who have made my stay here eventful and fun. Special thanks to Mr. Nicholas Goodman, for the intellectual discussions and both Nick and Wan for their friendship. I would also like to thank my whole CBM team (both graduate and undergraduate students) for truly making work a fun activity. Special thanks to Dr. Xiaomin Deng, for inciting an appreciation for beautiful concepts of Continuum Mechanics, Finite Element Methods, and Dr. Francis Gadala-Maria for introducing me to rheology of non-Newtonian fluids and his guidance in understanding their behavior. I would like to thank my friend Vamsi Annavajjula for patiently reviewing my thesis multiple times and providing valuable suggestions.
ABSTRACT

The CBM research at University of South Carolina is targeted at achieving some of the CBM objectives for rotorcrafts in collaboration with South Carolina Army National Guard. The current research study is motivated by the endeavor to enhance condition monitoring objectives by evaluating the condition indicators (CI) that have been implemented currently on the aircraft in operation.

For the purpose of this research three tail rotor gearbox have been tested to simulate severe lubricant starved conditions. The three test articles have failed in three different modes. The TGB article-1 had severe damage of the input gear teeth. For the second TGB article the testing was terminated when an input gear tooth broke. The third TGB article did not suffer significant damage to its gear teeth, but the testing was aborted due to an increase in temperature. For all the three articles, a significant increase in gear mesh second harmonics was observed but the condition indicators have not been successful in providing a warning well in advance. The only condition indicator that has triggered caution alarm was TGB lateral bearing energy CI. From the evaluation of condition indicators it is found that only the DA1 CI has shown a very sharp increase in its value. The FM0 and FM4 CI have also shown noticeable fluctuations but the variation was not severe to create any alarm. This suggests that if the existing CIs do not perform up to the expectations then an alternate CI that is either better in anticipating failure or produce similar results with relatively lower computational expense is beneficial.

In the current research, a new condition indicator that is relatively simpler compared to the FM4, ER, SLF, SI condition indicators and has the ability to offset some of the limitations of
Discrete Fourier transform (DFT) is proposed. The proposed CI is defined as Asynchronous to Synchronous Energy ratio in Time domain (ASET). As the name suggests, the ASET for a component rotating at a particular speed is obtained by dividing the total energy in the raw time domain signal with the energy in the time synchronous averaged signal of the component with synchronous frequency equal to the component’s frequency. The ASET CI has ability to identify modulation of synchronous frequencies, and change in gear mesh amplitudes. Since, the ASET CI does not involve any information about the spectrum of the signal, the need for DFT is eliminated which reduces computational burden as well as provides hope to detect the signals with both transient and periodic signal content. The proposed CI has been analyzed with the vibration data for the TGB article-2, TGB article-3 and the IGB article that was installed during the testing of TGB article-2 and TGB article-3. The plots obtained after computation of ASET for the test articles showed variation as hypothesized. Furthermore, ASET indicated existence of a functional relationship between FM0 and FM4 CIs.

This thesis presents the results of the experiment, evaluation of the existing CIs, the definition of the new CI and its behavior when fed with the data from the experiments conducted on test articles. The ASET CI can be a supplementary diagnostic algorithm that provides information about sidebands, gear mesh amplitudes from just the time-domain data. The proposed CI reacts to multiple failure modes with lower computational burden unlike some of the currently implemented CIs and hence has potential to substitute some of the existing CIs.
# TABLE OF CONTENTS

Dedication ........................................................................................................................................ ii

Acknowledgements ......................................................................................................................... iii

Abstract ........................................................................................................................................... iv

List of Figures .................................................................................................................................. x

List of Abbreviations .................................................................................................................... xiv

1 Introduction .............................................................................................................................. 1

1.1 Prelude ..................................................................................................................................... 1

1.2 Problem Definition ................................................................................................................ 1

1.3 Overview .................................................................................................................................. 2

1.4 Maintenance schema ............................................................................................................. 4

1.4.1 Run to Failure Management ......................................................................................... 4

1.4.2 Preventive Maintenance ............................................................................................... 5

1.5 CBM for US ARMY ............................................................................................................... 6

2 Condition Monitoring Theory and Techniques ........................................................................ 8

2.1 Vibration Analysis ............................................................................................................. 9

2.2 Digital Signal Acquisition ............................................................................................... 9

2.3 Time-domain analysis ...................................................................................................... 11

2.3.1 Root Mean Square (RMS) value: ............................................................................. 11
2.3.2 Maximum Amplitude................................................................. 12
2.3.3 Peak Level................................................................................... 12
2.3.4 Crest Factor ................................................................................ 13
2.3.5 Sideband Level Factor .............................................................. 13
2.3.6 Energy Ratio .............................................................................. 13

2.4 Frequency-domain Analysis .......................................................... 14
2.4.1 Fourier Transform ..................................................................... 14
2.4.2 Cepstrum Analysis .................................................................... 16

2.5 Gear Failure Prediction Techniques using Vibration data ............. 17
2.5.1 Gear mesh frequencies ............................................................... 17
2.5.2 Modulation and its influence ..................................................... 17
2.5.3 Time Synchronous Averaging ..................................................... 19
2.5.4 Residual Signal .......................................................................... 20
2.5.5 Difference Signal ...................................................................... 21
2.5.6 Band Pass Mesh Signal .............................................................. 21
2.5.7 Zero-order figure of merit ......................................................... 21
2.5.8 Kurtosis ..................................................................................... 22
2.5.9 Fourth-order figure of merit ....................................................... 23
2.5.10 Figure of Merit 4* ................................................................. 24
2.5.11 NA4 ....................................................................................... 24
2.5.12 NA4* ..................................................................................... 25
LIST OF FIGURES

Figure 2.1 Example of Aliasing problem ................................................................. 10

Figure 2.2 Peak and RMS amplitude of any arbitrary signal ................................. 12

Figure 2.3: Example of Leakage problem when representing infinite process using discrete Fourier transform[10] ................................................................. 15

Figure 2.4 Schematic representation of gear mesh frequency and its sidebands ......... 18

Figure 2.5 Example of time synchronous average derived from raw time signal [25] .... 20

Figure 2.6 Signal processing and computation of various fault diagnostic features [8] .... 27

Figure 3.1 Representation of TRDT components tested at USC CBM research center on AH-64D .................................................................................................................. 31

Figure 3.2 IGB, and TGB locations on vertical stabilizer of AH-64D ....................... 32

Figure 3.3 Schematic layout of AH-64D TRDT test stand at USC and data acquisition .... 34

Figure 3.4 AH-64D TRDT test stand at USC CBM research center ......................... 34

Figure 3.5 Accelerometer and Thermocouple locations on TGB .............................. 38

Figure 3.6 Accelerometers and Thermocouples location on IGB ............................... 39

Figure 3.7 TGB assembly cross section showing various sub-components[1] ............ 41

Figure 3.8 seeding procedure utilized to induce an output seal leak [1] .................... 42

Figure 4.1 Auto power spectrum of TGB article 1 in the initial phase of testing .......... 45

Figure 4.2 Auto power spectrum of TGB article 1 in the final phase of testing .......... 45

Figure 4.3 TGB article 1, borescopic pictures revealing heavy wear on the input gear of TGB [1] ...................................................................................................................... 46

x
Figure 4.4 TGB article 1, Lateral Bearing Energy CI across time towards the end of the run showing caution limit..................................................................................................................... 47
Figure 4.5 TGB Article 1, Vertical bearing energy CI after the cut seal towards the end of the run ....................................................................................................................................................... 47
Figure 4.6 TGB article 1, change in DA1, and DA2 over the whole period of testing ............... 48
Figure 4.7 TGB article 1, Figure of Merit group CIs for input 22T and output 57T gears over the whole period of testing............................................................................................................................................ 49
Figure 4.8 TGB article 1, input and output gears’ sidebands based CIs variation over duration of testing........................................................................................................................................................................... 49
Figure 4.9 TGB article 1, input and output gears’ energy ratio based CIs variation over duration of testing ........................................................................................................................................................................... 50
Figure 4.10 TGB article 1, input and output gears’ DA3 variation over the duration of testing .. 50
Figure 4.11 TGB Article 2, input gear after one of its tooth broken and the other tooth addendum was also damaged [1] ........................................................................................................................................................................... 52
Figure 4.12 Auto power spectrum of TGB article 2, in the initial phase of experiment ........................................................................................................................................................................................................ 53
Figure 4.13 Auto power spectrum of the TGB article 2, prior to failure .............................. 53
Figure 4.14 TGB article 2, Lateral Bearing energy CI across time, towards the final phase before failure ............................................................................................................................................................................................................ 54
Figure 4.15 TGB article 2, change in DA1, and DA2 over the whole period of testing ............ 55
Figure 4.16 TGB article 2, Figure of Merit group CIs for input 22T and output 57T gears over the whole period of testing............................................................................................................................................................................................................. 55
Figure 4.17 TGB article 2, input and output gears’ sidebands based CIs variation over duration of testing .............................................................................................................................................................................................................. 56
Figure 4.18 TGB article 2, input and output gears’ energy ratio based CIs variation over duration of testing .............................................................................................................................................................................................................. 56
Figure 4.19 TGB article 2, input and output gears’ DA3 variation over the duration of testing ... 57
Figure 4.20 TGB article 3, borescope pictures after the final phase of testing [1] ................. 58
Figure 4.21 Auto power spectrum of TGB article 3, during initial phase of testing............... 59
Figure 4.22 Auto power spectrum of TGB article 3 prior to the end of testing..................... 59
Figure 4.23 TGB article 2, Lateral Bearing energy CI across time, towards the final phase before failure ............................................................................................................................................. 60
Figure 4.24 TGB article 3, change in DA1, and DA2 over the whole period of testing.......... 60
Figure 4.25 TGB article 3, Figure of Merit group CIs for input 22T and output 57T gears over the whole period of testing................................................................................................................... 61
Figure 4.26 TGB article 3, input and output gears’ sideband analysis based CIs ................. 61
Figure 4.27 TGB article 3, input and output gears’ energy ratio based CIs variation over duration of testing ........................................................................................................................................ 62
Figure 4.28 TGB article 3, input and output gears’ DA3 variation over the duration of testing ... 62
Figure 5.1 Generic non-periodic sample set that could create spectral leakage .................. 65
Figure 5.2 Distribution of Gaussian noise[11] ........................................................................ 66
Figure 5.3 Comparison of ASET of input 37T and output 49T gears' of IGB test article .......... 70
Figure 5.4 IGB article, Comparison of ASET of input gear with linear combination of FM0, FM4 CIs of input gear ............................................................................................................................................. 71
Figure 5.5 IGB article, Comparison of ASET of output gear with linear combination of FM0, FM4 CIs of output gear ............................................................................................................................................. 71
Figure 5.6 ASET ratios for input 22T gear, output 57T gear over the whole duration of experiment ............................................................................................................................................. 72
Figure 5.7 Comparison of ASET input gear with a linear combination of FM0, FM4 CIs of input gear............................................................................................................................................................................................................. 73
Figure 5.8 Comparison of ASET of output gear with a linear combination of FM0, FM4 CIs of output gear ............................................................................................................................................................................................................. 74
Figure 5.9 Comparison of ASET ratios for input and output gear for the whole duration of experiment ..................................................................................................................................... 75

Figure 5.10 Comparison of ASET of input gear with linear combination of FM0 and FM4 CIs of input gear .................................................................................................................................................. 76

Figure 5.11 Comparison of ASET of output gear with linear combination of FM0, FM4 condition indicators of output gear ........................................................................................................................................ 77
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBM</td>
<td>Condition Based Maintenance</td>
</tr>
<tr>
<td>CI</td>
<td>Condition Indicator</td>
</tr>
<tr>
<td>USC</td>
<td>University of South Carolina</td>
</tr>
<tr>
<td>TRDT</td>
<td>Tail Rotor Drive Train</td>
</tr>
<tr>
<td>VMEP</td>
<td>Vibration Management Enhancement Program</td>
</tr>
<tr>
<td>TGB</td>
<td>Tailrotor GearBox</td>
</tr>
<tr>
<td>IGB</td>
<td>Intermediate GearBox</td>
</tr>
<tr>
<td>FHB</td>
<td>Forward Hanger Bearing</td>
</tr>
<tr>
<td>AHB</td>
<td>Aft Hanger Bearing</td>
</tr>
<tr>
<td>HUMS</td>
<td>Health and Usage Management Systems</td>
</tr>
<tr>
<td>IAC</td>
<td>Intelligent Automation Corporation</td>
</tr>
<tr>
<td>MSPU</td>
<td>Modernized Signal Processing Unit</td>
</tr>
<tr>
<td>GBS</td>
<td>Ground Based System</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
</tr>
<tr>
<td>MTF</td>
<td>Maintenance Test Flight</td>
</tr>
<tr>
<td>RUL</td>
<td>Remaining Useful Life</td>
</tr>
<tr>
<td>RPM</td>
<td>Rotations Per Minute</td>
</tr>
<tr>
<td>FPG</td>
<td>Flat Pitch Ground</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>Max</td>
<td>Maximum</td>
</tr>
<tr>
<td>Min</td>
<td>Minimum</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>DIF</td>
<td>Difference Signal</td>
</tr>
<tr>
<td>RES</td>
<td>Residual Signal</td>
</tr>
<tr>
<td>RMSDS</td>
<td>Root Mean Square value of Difference Signal</td>
</tr>
<tr>
<td>RMSRC</td>
<td>Root Mean Square value of Residual Signal</td>
</tr>
<tr>
<td>FT</td>
<td>Fourier Transform</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>HT</td>
<td>Hilbert Transform</td>
</tr>
<tr>
<td>FM</td>
<td>Figure of Merit</td>
</tr>
<tr>
<td>DA</td>
<td>Diagnostic Algorithm</td>
</tr>
<tr>
<td>PPA</td>
<td>Peak to Peak Amplitude</td>
</tr>
<tr>
<td>TSA</td>
<td>Time Synchronous Averaging</td>
</tr>
<tr>
<td>SLF</td>
<td>Sideband Level Factor</td>
</tr>
<tr>
<td>SI</td>
<td>Sideband Index</td>
</tr>
<tr>
<td>FOSL</td>
<td>First Order Sideband Levels</td>
</tr>
<tr>
<td>CF</td>
<td>Crest Factor</td>
</tr>
<tr>
<td>ER</td>
<td>Energy Ratio</td>
</tr>
<tr>
<td>BPM</td>
<td>Band Pass Mesh signal</td>
</tr>
<tr>
<td>STFT</td>
<td>Short Time Fourier Transform</td>
</tr>
<tr>
<td>MIL</td>
<td>Military</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>Lat</td>
<td>Lateral</td>
</tr>
<tr>
<td>Vert</td>
<td>Vertical</td>
</tr>
<tr>
<td>ASET</td>
<td>Asynchronous to Synchronous Energy ratio in Time domain</td>
</tr>
<tr>
<td>ATS</td>
<td>Asynchronous Time Signal</td>
</tr>
</tbody>
</table>
T Teeth
1 INTRODUCTION

1.1 PRELUDE

The primary objective of condition-based maintenance (CBM) strategy is to identify the failure prior to its occurrence such that an appropriate action can be pursued since the failure is anticipated. An important requirement of any condition indicator is its ability to react to an impending failure without ambiguity. Its implementation for real time condition monitoring warrants it to be computationally less expensive and rapid. Hence, even though advanced time frequency analysis metrics are available, the conventional condition monitoring algorithms are still popular for the practical applications.

1.2 PROBLEM DEFINITION

In the current research study experiments were conducted on tail rotor gearbox starved from lubrication with an objective to evaluate if the currently implemented condition indicators show any indication of the health of the component prior to failure. As expected all the gearboxes have suffered degradation of their health and have been terminated after they met the failure criterion [1]. To our surprise, the condition indicators of the tail rotor gearbox that are expected to provide an alarm did not perform their functions effectively.

Considering the functional definition of various CIs and the related computational expense for their implementation the inefficacy of the CIs in indicating the health of the component is not very useful. Hence an alternative condition indicator that either performs effectively than the existing condition indicator algorithms, or is computationally less expensive
to implement and offers advantages that offsets the limitations of existing CI could be beneficial for advancement of CBM.

1.3 OVERVIEW

The thesis is based upon the experimental work and the theoretical investigation of the condition monitoring techniques that provide the ability to identify the impending failure. Most of the experimental data is generated from the Apache AH-64 tail rotor drive train (TRDT) test stand at the University of South Carolina’s (USC) condition-based maintenance (CBM) research center. It is also designed to emulate the loads and worst case scenarios for AH-64 tail rotor drive train components that could be experienced by AH-64 in operations.

A typical VMEP equipment installed AH-64 rotorcraft in service with the US-Army has accelerometers installed at various critical locations. The USC TRDT test stand emulates the condition monitoring schema of VMEP installed AH-64. More specifically the current research is focused on the intermediate gearbox (IGB) and the tail rotor gearbox (TGB) of the AH-64 rotorcraft due to the frequent maintenance activity on them and the expense involved. This data is acquired by the Intelligent Automation Corporation’s (IAC) modernized signal processing unit (MSPU), which further processes the data and computes the features with the fault information which are represented in the form of parameters, known as the Condition Indicators (CIs). Further these condition indicators can be analyzed for change over time using the application software developed by IAC, known as the PC-Ground Based System (PC-GBS) [2,3,4]. The data acquired is evaluated for change in the pre-defined CI trends over the test duration, and compared with the gear diagnostic methodologies applied on the raw time signal.

This research presents the results of evaluation of the current condition monitoring techniques. The analytical work also consists of exploring an alternative indigenous algorithm based on the time domain information only and contrasting it with various existing gear condition
monitoring CIs. The proposed algorithm is computationally less expensive relative to implementation of the most of the existing CIs and it also yields similar information that is obtained from the FM0, FM4 and SI condition indicators.

The thesis is divided into six chapters such that the information from the current research is presented in modular form. The current chapter (Chapter 1) presents the problem definition, overview of the thesis, brief ideas of the various maintenance schemas, and significance of the condition-based maintenance for the rotorcraft.

Chapter 2 covers basic theory of digital signal processing, typical vibration phenomenon in geared transmission, analytical and statistical signal processing techniques for vibration that are employed over years and the related literature review.

Chapter 3 gives a description of the TRDT test stand, component details, sensors and Data Acquisition system (DAQ) specifications, operating conditions of TRDT test stand, and specifications of the employed lubricants.

Chapter 4 concentrates on experimental work conducted, and summarizes the results of frequency responses/power spectrums and the inferences from the inspection of the components. Results of applying the proposed technique which is based on anomaly detection, and existing gear diagnostic techniques in the form of CIs are all presented in Chapter 5.

Chapter 6 marks the culmination of all the research I have pursued and the possible applications and benefits for the proposed technique and recommendations applicable for further investigation.
1.4 MAINTENANCE SCHEMA

The design of the mechanical systems is conceived with the specific tasks that have to be accomplished. The failure of the mechanical systems does not mean a complete breakdown of the system. It can be defined as the inability of a system to perform its functions up to the expectations. Every mechanical systems age, and they eventually lead to the failure after certain operational time. To reduce the impact of mechanical systems aging effects on the whole system, various maintenance schemas are implemented depending upon the impact of failure, cost of the maintenance program and various other parameters of concern. Essentially any maintenance programs’ primary goal is to assess the health of the component in performing its functions normally, and take corrective measures that would not hinder the systems’ performance. All these maintenance philosophies vary by the strategies and the principles. These can be broadly classified into three types [5].

1.4.1 RUN TO FAILURE MANAGEMENT

As Mr. Mobley, describes in his book on Predictive Maintenance, the whole idea behind the run to failure management’s strategy is summarized in the statement: “If it ain’t broke, don’t fix it” [5]. This is a reactive approach to maintenance and is most likely a choice for any organization in whose case fixing a failed component is less expensive than investing its time and money in the maintenance programs. Nevertheless this is not a choice for the organizations for whom being operational is crucial either due to the mission at hand or due to the liabilities and losses that would be incurred otherwise. Also, the run to failure management is not necessarily less expensive if the failure is catastrophic. Hence the other maintenance management philosophies evolved.
1.4.2 PREVENTIVE MAINTENANCE

The preventive maintenance programs typically attempt to service the system prior to failure after a finite operational life instead of leaving the system to break eventually. This can be further classified to two categories.

1. Schedule-based maintenance

2. Condition-based maintenance.

1.4.2.1 Schedule-based Maintenance

In schedule-based maintenance, the system and its components are inspected and serviced at regular time intervals. The idea behind this strategy is that every component degrades over finite amount of operational time. If the component is serviced just before it is completely degraded, the life of the component can be extended further. This definitely offers advantages over run to failure management philosophy as the subsystem is not yet broken, and hence the whole system that depends on this subsystem/component does not have to suffer downtime.

The crucial element in the schedule-based maintenance is estimating the maintenance schedule. But the maintenance schedule need not be standard for all components as every component might have a different operational life. When mandatory replacements are performed after fixed time interval, sometimes even the healthy components are replaced thus not utilizing the component to its full life. Also if the operating conditions change the failure modes also change and the estimated time schedule would be neither safe for meeting the functional requirements nor is optimum thus reducing the efficiency of the maintenance program. Hence the need for condition-based maintenance aroused.
1.4.2.2 Condition-based Maintenance

As the name suggests, the system or its components are serviced/repaired only when the need arises. The crucial element of CBM is identifying when the need has risen. This is accomplished by monitoring the system’s condition and judging if it needs to be serviced, or if it can operate for additional time. Depending on the device which is being monitored, there exists wide variety of condition monitoring technologies and techniques that can be utilized. The most common technologies include vibration monitoring, thermography, tribology, and ultrasonic measurements. Vibration monitoring is most frequently utilized on the rotating and the reciprocating mechanical systems. Tribological measurements can be used to monitor debris particles within a lubricant or even determine the quality of the lubricant itself. Ultrasonic sensors are employed in detection of acoustic emission signals from the static structures and shock pulse phenomenon from the rotating machinery.

The sensors play a major role in reporting the raw data about the health of the system and its components, thereafter advanced analysis on this raw data reveals vital information about the condition of the system and its components.

1.5 CBM FOR US ARMY

CBM for the Army Aviation’s is expected to improve the availability, safety, quality, reduce the maintenance burden, and provide the information and analysis necessary to optimize the maintenance supply chain. To a commander in the field, CBM translates into the ability to meet mission requirements with proactively driven maintenance and thereby increasing operational availability [6]. But to an aircraft mechanic, CBM is the ability to convert data on the aircraft condition and use in proactive maintenance action, and therefore reducing the maintenance workload. The CBM is intended to identify the faults with a sufficient lead time so that the ground maintainer can schedule corrective actions well before the fault matures to a failure. Many of the inspections require removal of the critical parts which when reinstalled
require a maintenance test flight (MTF). By eliminating these types of inspections, MTFs could be reduced. Since MTFs represent significant portion of maintenance costs, curtailing MTFs results in cost savings.

For the AH-64 fleet, US Army implements the vibration management enhancement program (VMEP) & the health usage monitoring systems (HUMS) to assist in assessing the remaining useful life (RUL) before a component is serviced or replaced [7]. The RUL is a function of health and usage. A typical AH-64 has the accelerometers installed at various critical locations from which vibration data is periodically collected by MSPU. The MSPU further analyzes this data and computes a collection of diagnostic metrics known as condition indicator (CI) functions. These functions are typically model-based, and they attempt to extract information about a particular physical process or an event such as shock impulses, ball spin and gear mesh frequencies, and amplitudes. The primary function of the VMEP system is to assist in routine maintenance functions such as rotor smoothing, and mandatory vibration checks. The PC-GBS software system displays recommended maintenance actions on the aircraft, reports aircraft status to the maintenance manager and measurement details to the engineer. Typically during maintenance, a test run on the helicopter is performed on ground with the main rotor blades having a flat pitch and rotating at 101% of the nominal speed of the main rotor. This is known as the FPG 101 load condition. The TRDT stand at the CBM research center at USC simulates a specific load profile designed according to the test plan. This load profile includes multiple intermediate load changes to FPG 101 loading condition after every 50 minutes. The asynchronous time domain data is collected during the FPG101 loading condition.
Rotorcrafts in operation are exposed to changing mechanical loads, varying environments involving fluctuations in the temperature, humidity, and convection that initiate and propagate the regular as well as the fatigue damage to various components. Condition monitoring of various components is highly dependent on the state of the art sensors and the fundamental understanding of failure modes and the diagnostics techniques. Accelerometers are the popular sensors for condition-based maintenance both due to the advancements in application of vibration analysis as well as the ability of sensors to capture broad range of frequencies. Gearboxes and bearings have been some of the common power transmission components employed in various conveyance systems as well as vehicles. There has been significant amount of research performed for the development of diagnostic techniques for gearboxes and bearings. The result of this research over previous couple of decades is introduction of statistical techniques, combined statistical and spectroscopic techniques and application of time-frequency analysis for rotating machinery. A Condition Indicator (CI) can be defined as a parameter that is sufficiently sensitive to a certain failure mode and should be able to trigger an early alarm [8]. The most appropriate technique(s) for diagnosis is chosen based on the operating conditions, resources available and the degree of criticality of the machine component. A review of the diagnostic techniques, theory of digital signal processing is presented in this chapter to give the reader some background into the methods used in the current analysis.
2.1 VIBRATION ANALYSIS

It is long believed that the presence of a fault in an equipment or machinery while still in its incipient phase will be accompanied by a detectable increase or modification of vibration signatures. An anomaly in vibration signals of a component compared to the baseline vibration signatures reveals earliest symptoms [9,10]. The theory about vibration theory has been presented in various books. Hence here only signal processing techniques and diagnostic algorithms are discussed.

2.2 DIGITAL SIGNAL ACQUISITION

An analog signal is a signal that is continuous in both time and amplitude. In contrast, a digital signal is discrete in both the time and the amplitude. To convert a signal from the continuous time domain to the discrete time domain signal, the analog signal is sampled at certain intervals of time [11]. Each individual measurement is referred as a sample and the process is referred as sampling. Sampling has a predominant influence on the digital vibration signal acquired. The vibration time domain data is obtained by sampling the output from the sensors (accelerometers, acoustic emission sensors) at constant time increments. The amount of information that can be obtained with minimum errors is limited, and it is dictated by the Nyquist-Shannon sampling theorem, and the Raleigh Criterion [10]. Nyquist Criterion states that the sampling frequency (number of samples acquired per second) must be at least twice the maximum frequency of interest. Hence, the highest frequency detectable in a signal is dictated by the Nyquist criterion, and it is a common practice to call this highest detectable frequency as the Nyquist frequency.

\[ f_{max} = f_s/2 \]

Where \( f_{max} \) is the Nyquist frequency \( f_s \) is the sampling frequency
Raleigh’s criterion states that the lowest frequency component measurable or the ability to resolve two frequencies that are closely spaced is given by the following equation.

\[ f_{\text{min}} = \frac{1}{T} \]

Where

<table>
<thead>
<tr>
<th>( f_{\text{min}} )</th>
<th>is the minimum frequency component that is measurable</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T )</td>
<td>is the length of the time record in seconds</td>
</tr>
</tbody>
</table>

If the sampling frequency is lower than the Nyquist frequency, a phenomenon known as aliasing is exhibited. Aliasing is essentially the problem in distinguishing different signals. It occurs if the sampling frequency is not sufficient enough as a result of which the frequency inferred would be different from the actual signal (Figure 2.1).

![Aliasing Example](image)

Figure 2.1 Example of Aliasing problem

The error in measurement as a result of sampling process can be divided into two categories, variance and bias. Variance is the measure of deviation from the expected value. The primary contribution to variance is due to the noise in the signal and the accuracy of measurement equipment. Bias errors are as a result of limitations in expressing infinite process with finite
information, eg. Aliasing. Signal conditioning using filters, windowing, and normalization are often employed to enhance the signal to noise ratio thus improving the quality of the signal.

The vibration data in its raw form is not easy to decipher due to multiple and overlapping sources of vibration. Hence it is difficult to analyze in this form and does not reveal significant details. To address this problem, various signal processing techniques are applied on the raw data obtained from the sensors. Signal processing techniques constitute the algorithms that are applied to the signals to provide insight for further interpretation of measured data. These techniques can be classified into time domain analysis, frequency domain analysis, statistical, and time-frequency analysis [12].

2.3 TIME-DOMAIN ANALYSIS

The time-domain analysis is a native data analysis technique in its raw form as the output from various vibration sensors is in discrete time domain data. It is computationally less expensive to implement and the only preprocessing needed is conditioning the signal. Time domain analysis is well suited for stochastic signals and transient phenomenon. In this section, some of the statistical analysis techniques performed on time domain data is presented [13].

2.3.1 ROOT MEAN SQUARE (RMS) VALUE:

The root mean square (RMS) value of a signal is directly proportion to the energy of the signal. The RMS feature is good technique to track overall noise level and is a measure of power content in the vibration signature, but it does not provide any information about any specific component. It is useful in detecting any major out of balance in the rotating systems. Sometimes, difference in RMS value of baseline or previous signal and the current signal is also used as a diagnostic feature. The RMS of a signal \( x(n) \) is given by
2.3.2 MAXIMUM AMPLITUDE

The maximum amplitude is directly evident from the time domain signal as shown in Figure 2.2. This is in general an indicative of bearing defect in bearings or severe defect in gear mesh.

![Figure 2.2 Peak and RMS amplitude of any arbitrary signal](image)

2.3.3 PEAK LEVEL

The peak level of a signal is computed as half the difference between maximum and minimum amplitudes of the signal.

\[
    \text{Peak} = \frac{1}{2} \left( \max(x(t)) - \min(x(t)) \right)
\]

Where \( x(t) \) is any arbitrary signal in time domain.
2.3.4 CREST FACTOR

The crest factor (CF) is defined as the ratio of Peak level (PL) to RMS. This feature is useful in detecting changes in the signal pattern due to any impulse signal in the vibration signal. The impact sources could be due to damage to gear tooth, bearing race defect, etc. The source signal for computing CF in VMEP is synchronous time domain data instead of the actual asynchronous time domain signal acquired. This technique performs better than RMS but it not considered as a sensitive technique. The CF is mathematically computed by

$$CF = \frac{PL}{RMS}$$

2.3.5 SIDEBAND LEVEL FACTOR

The sideband level factor, (SLF), is an indicator of single tooth damage or gear shaft damage. This is computed by performing the ratio energy in first order sideband levels (FOSL) about the primary meshing frequency to the RMS of the signal.

$$SLF = \frac{FOSL}{RMS}$$

2.3.6 ENERGY RATIO

The energy ratio (ER) is expected to indicate heavy uniform wear. This is defined as the ratio of RMS of the difference signal (RMSDS) to the RMS of the signal composed of the regular frequency components (RMSRC).

$$ER = \frac{RMSDS}{RMSRC}$$
2.4 FREQUENCY-DOMAIN ANALYSIS

The frequency-domain analysis is the popular and widely used technique for diagnostics using vibration data. This is performed by transforming the raw time series data into the frequency domain using integral transforms. The periodic signals are best analyzed in frequency domain. The Fourier transform is one of the most popular tools employed for vibration analysis in the frequency domain. The other prevalent techniques include, Laplace transform, and Z-transform.

2.4.1 FOURIER TRANSFORM

The foundation for the Fourier transform stems from the Fourier series. Fourier series provides mathematical framework to express any continuous time domain signal as a series of sine and cosine functions of various amplitudes, frequencies and phase relationships [14]. Fourier transform is a mathematical operation whereby a signal can be decomposed into constituent frequencies with varying amplitudes. It is a lossless transformation where only the dependant variable is changed from time to frequency. Identifying the frequency content of a signal is extremely beneficial in analyzing the rotating components. The forward Fourier transform is expressed mathematically by the following equation.

\[ F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j2\pi\omega t} \, dt \]

Where \( f(t) \) is any arbitrary signal in time domain

\( F(\omega) \) is the representation of \( f(t) \) in frequency domain

The time domain signal can be reconstructed using the inverse Fourier transform what is mathematically expressed as shown in the following equation.

\[ \mathcal{F}^{-1}(\omega) = f(t) = \int_{-\infty}^{\infty} F(\omega) e^{-j2\pi\omega t} \, d\omega \]
The limits of integration in the classical form of Fourier transform range from negative to positive infinity, but the experimental data is finite. Hence Discrete Fourier Transform (DFT) is used with experimental data [15]. The forward DFT and the inverse DFT is mathematically computed as shown in the following equations respectively.

\[
F_n = \sum_{k=0}^{N-1} f_k e^{-\frac{j2\pi kn}{N}} \quad \text{(Forward transform)}
\]

\[
 f_k = \sum_{n=0}^{N-1} f_k e^{-\frac{j2\pi kn}{N}} \quad \text{(Inverse transform)}
\]

To implement the DFT, the signal is assumed to be totally observed transient or completely periodic within the time period of observation, and the signal must be composed of harmonics only during the time period of observation. Since, it is not always possible to meet both the criterion at all times, DFT results in leakage, a bias error, as shown in Figure 2.3.

![Figure 2.3: Example of Leakage problem when representing infinite process using discrete Fourier transform [10]](image)

The Fast Fourier Transform (FFT) is an efficient algorithm to compute DFT which not only results in significant reduction of computational time but also retains the phase information.
The FFT technique is one of the major driving forces for embracing frequency domain analysis for vibration diagnostics in the past when the computational resources are precious.

### 2.4.2 CEPSTRUM ANALYSIS

The Cepstrum is defined as the inverse FFT of the logarithm of the auto power spectrum. The Cepstrum analysis is a tool for detecting periodicity in a frequency spectrum[16]. Cepstrum analysis is useful in identifying harmonics in a signal, and it also finds application in cases where the vibration spectrum is modulated resulting in sidebands in frequency spectrum. The Cepstrum of a signal is mathematically computed by the following equation.

\[
C_p(\tau) = \text{FFT}^{-1}(\log[S_{xx}(f)])
\]
2.5 GEAR FAILURE PREDICTION TECHNIQUES USING VIBRATION DATA

The various sources that influence the vibration signature of gearbox include, meshing of gear teeth, tooth fatigue, debris inclusions, fluctuations in torque, amplitude or frequency modulations etc. They can occur independently or simultaneously depending upon the nature of failure. There is no diagnostic technique that exactly identifies the source causing a fault, nevertheless from maintenance perspective it is adequate to identify the fault. In this section two of the most common phenomenon related to gear vibration is presented. This is followed by a review of various gear failure prediction techniques that are popular for condition monitoring of geared systems [9,17,18,19,20].

2.5.1 GEAR MESH FREQUENCIES

Every gear set generates a unique profile of frequency components which is highly dependent upon the speed of rotation of the participating gears [13]. It can be understood that the gear-mesh frequencies appear as transients in the spectrum when the transmission is subjected to angular acceleration and as harmonics when the transmission is operating under steady speed. The fundamental gear-mesh frequency is the product of number of teeth of the gear and its speed of rotation. The amplitudes of gear-mesh frequency components are strong function of the torque transmitted by participating gears, and any modulating effects on them.

2.5.2 MODULATION AND ITS INFLUENCE

Vibration spectra of machines have their energy distributed in multiple frequencies. In geared transmission systems, mesh-force modulation is a commonly observed phenomenon
The modulation processes transfer energy from the actual frequency to the sidebands about the gear mesh fundamental frequency and its harmonics. In rotating systems, for every harmonic, multiple sidebands are observed about each harmonic and they are symmetrically spaced about the harmonics and decay exponentially as the sideband orders separate farther away from the gear-mesh frequency. The sidebands need not be symmetric [23]. This spectral information when analyzed in detail provides significant information about gear tooth condition as well fluctuations in drive system and the condition of the bearings in the gearbox. These sidebands can be caused by Amplitude modulation, phase modulation or frequency modulation, or a combination of them. The concept of modulation is quite researched and extensive literature regarding this phenomenon is available in communication systems. The carrier frequency and the message signal referred in communication systems are analogous to primary frequency (gear-mesh or its harmonics) and the modulating signal respectively. Phase modulation is the deviation in phase from the linearly increase phase of the carrier, while frequency modulation is the difference in the instantaneous frequency from the constant carrier frequency. The modulating components often manifest as sidebands surrounding the gear-mesh harmonics as shown in Figure 2.4

![Figure 2.4 Schematic representation of gear mesh frequency and its sidebands](image)
2.5.3 TIME SYNCHRONOUS AVERAGING

Time Synchronous Averaging (TSA) enables extraction of periodic waveforms from noisy signals [24]. The technique is ideal for gearboxes as it helps in separating the vibration signature of a single gear from the complete spectrum. This process requires a trigger signal that is synchronous with the desired signal, typically the rotating shafts. The raw data obtained is divided into equal segments with their lengths related to the synchronous signal and averaged together. In principle, when sufficient averages are taken, the random noises as well as the frequencies which are not the orders of synchronous signal are cancelled and the desired signal estimate is improved [25]. Each segment begins based on the leading edge of the tachometer pulse, and ends on the corresponding data point that precedes the next tachometer pulse. The final step is to average all the segments and transform back to the original sampling rate, as shown in Figure 2.5. TSA quality is affected by interpolation factor which is used to increase the number of data points in the series before segmentation, total number of averages and number of revolutions concatenated during the alignment. Increasing the number of averages is not always a solution to improve TSA due to expense involved in computations. Nevertheless anomalies in desired signal are easily detectable from TSA, due to high signal to noise ratio, hence is an attractive technique for gear and bearing diagnostics.
2.5.4 RESIDUAL SIGNAL

The residual signal (RES) consists of TSA signal with the primary meshing and shaft components along with their harmonics removed. There is still some ambiguity about number of harmonics that needs to be removed for shaft and mesh components but it is suggested to have a high pass filter that filters all frequencies except those that lie between DC and fundamental meshing frequency.
2.5.5 DIFFERENCE SIGNAL

The difference signal is computed by removing the regular meshing components from the TSA signal. The regular meshing components include, shaft frequency and its harmonics, gear mesh frequency and its harmonics along with the first order sidebands. To summarize residual signal is difference signal with all first order sidebands of primary meshing frequency included in it.

2.5.6 BAND PASS MESH SIGNAL

The band pass mesh (BPM) signal is obtained by applying the band pass filter to the TSA signal around the primary gear mesh frequency including all significant sidebands [10]. The Hilbert transform is then applied to the filtered signal. This produces a complex time series whose real part is the band pass signal and imaginary part is Hilbert transform of the signal. The envelope is represented by the magnitude of the complex time series signal and it gives an estimate of amplitude modulation [26].

\[ E(t) = \sqrt{A(t)^2 + H[A(t)]^2} \]

Where \( E(t) \) is the envelope band-passed signal
\( A(t) \) is the band-passed signal
\( H[A(t)] \) is the Hilbert transform of the band-passed signal

2.5.7 ZERO-ORDER FIGURE OF MERTI

The zero-order figure of merit, FM0 is a global technique that will react to changes in the whole frequency span of the average and identifies major anomalies in meshing pattern. It is defined as the ratio of peak to peak amplitude (PPA) of the TSA signal to the sum of amplitudes
of gear mesh frequency and its harmonics. An increase in peak to peak level is generally observed in case of major tooth faults, such as tooth breakage without significant change in the mesh frequency. This results in increase of FM0 value. In case of heavy uniform wear, the peak to peak does not change appreciably but the meshing frequencies tend to decrease which also results in increase of FM0 value. In heavy wear situations, when the surface quality degrades significantly and the gear tooth profile is affected, the meshing energy is redistributed from the meshing frequencies to the modulating sidebands which further results in FM0 values to increase. But FM0 fails to be a good indicator in minor tooth damage situations as both peak to peak levels and meshing frequencies do not have a significant change. FM0 is relatively insensitive to torque changes but not speed, and it is tolerant of accelerometer positioning error. The mathematical expression for FM0 is as follows.

\[
FM0 = \frac{PPA_{TSA}}{\sum_{i=1}^{n} A(f_i)}
\]

Where

- \(FM0\) is the zero-order figure of merit
- \(PPA_{TSA}\) is the peak to peak value of the vibration signal of TSA in the time domain
- \(A(f_i)\) is the amplitude of the \(i\)-th harmonic of the gear mesh frequency

2.5.8 KURTOSIS

Kurtosis is defined as the fourth moment of the distribution, and is a measure of the relative peakedness of a distribution [27]. It is used as an indicator of major peaks in a data set. This feature is expected to increase when gears wear down and when they break. The Kurtosis metric by itself is not a good measure of condition, hence a normalized Kurtosis is expected to make it independent of the individual article.
2.5.9 FOURTH-ORDER FIGURE OF MERIT

The fourth-order figure of merit, FM4 metric uses standard deviation and kurtosis of the difference signal obtained by subtracting the regular meshing components from TSA signal [10]. The absolute kurtosis mentioned previously is proportional to the standard deviation. Hence it increases with increase in standard deviation. To overcome this drawback the absolute kurtosis is normalized by dividing it with fourth power of standard deviation thus making it non-dimensional as well.

When a gear is in good condition, the difference signal would be primarily noise with Gaussian amplitude distribution and the standard deviation should be relatively constant. When there is severe damage to tooth, a peak or series of peaks appear in difference signal. In these circumstances both the kurtosis and standard deviation would increase. Hence normalized Kurtosis, or FM4, serves as a better indicator and is more sensitive to inception and severity of single tooth defects. The mathematical equation for computation of FM4 is as follows

\[ K = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^4 \]

Where

- \( K \) is the Kurtosis of signal \( x \) of length \( N \)
- \( x_i \) is the amplitude of the signal of the \( i \)-th sample
- \( \bar{x} \) is the arithmetic mean of the signal \( x \)
\[ FM4 = \frac{N \sum_{i=1}^{N} (d_i - \bar{d})^4}{(\sum_{i=1}^{N} (d_i - \bar{d})^2)^2} \]

Where

- \( FM4 \) is the fourth-order figure of merit
- \( d_i \) is the amplitude of the \( i \)-th point of the difference signal
- \( \bar{d} \) is the arithmetic mean of the difference signal \( d \)
- \( N \) is the length of the difference signal

2.5.10 FIGURE OF MERIT 4*

FM4* is an enhanced version of FM4 where the denominator in FM4 function is replaced with square of the variance of the difference signal of the baseline (good) gearbox.

2.5.11 NA4

NA4 is the ratio of kurtosis of the residual signal to the current run time averaged variance of the residual signal [13]. It was developed to detect the onset of damage and it is expected to continue to react as the damage progresses. The equation to compute NA4 is given by the following equation.

\[ NA4 = \frac{N \sum_{i=1}^{N} (r_i - \bar{r})^4}{(\frac{1}{M} \sum_{j=1}^{M} (\sum_{i=1}^{N} (r_i - \bar{r})^2))^2} \]

Where

- \( r_i \) is the amplitude of the \( i \)-th point of the residual signal
- \( \bar{r} \) is the arithmetic mean of the residual signal \( r \)
- \( M \) is the current time record number
- \( N \) is the length of the residual signal
2.5.12 NA4*

NA4* is an improved version of NA4 where the Kurtosis of the residual signal is normalized with the residual signal variance for a gearbox in good condition instead of the running variance used in NA4. The equation for NA4* is as follows

\[ NA4* = \frac{1}{N} \sum_{i=1}^{N} (r_i - \bar{r})^4 }{(\bar{M}_2)^2} \]

Where
- \( r_i \) is the amplitude of the \( i \)-th point of the residual signal
- \( \bar{r} \) is the arithmetic mean of the residual signal \( r \)
- \( \bar{M}_2 \) is the variance of the residual signal for a gearbox in good condition
- \( N \) is the length of the residual signal

2.5.13 NB4

NB4 is similar to NA4. But instead of the residual signal, the envelope of a band-passed signal of the TSA signal obtained by Hilbert transform is used. The theory driving this is that a few damaged gear teeth cause fluctuations in load which are transient and are different from the normal tooth load fluctuations. These fluctuations are expected to be observed in the envelope of a signal which is band-pass filtered about the dominant meshing frequency. (refer section 2.5.6)

NB4 is the ratio of the Kurtosis of the envelope signal to the square of the current run time averaged variance of the envelope signal.
\[ NB4 = \frac{N \sum_{i=1}^{N} (E_i - \bar{E})^4}{\left( \frac{1}{M} \sum_{j=1}^{M} \left[ \sum_{i=1}^{N} (E_{ij} - \bar{E}_j)^2 \right] \right)^2} \]

Where

- \( E \) is the envelope of the band-passed signal
- \( \bar{E} \) is the arithmetic mean of the band-passed signal
- \( M \) is the current time record number
- \( N \) is the length of the band-passed signal

2.5.14 NB4*

NB4* is same as NB4 where the denominator is replaced with the envelope signal variance for a gearbox in good condition instead of the running variance used in NB4.

2.5.15 M6A AND M8A

These metrics are proposed to detect surface damage on machinery components. These features are applied to the difference signal, and are expected to be sensitive to peaks in the difference signal. M6A and M8A are similar to FM4, except for the order of the statistical moment and the exponent of the normalizing variance

\[ M6A = \frac{N \sum_{i=1}^{N} (d_i - \bar{d})^6}{[\sum_{i=1}^{N} (d_i - \bar{d})^2]^3} \]

\[ M8A = \frac{N \sum_{i=1}^{N} (d_i - \bar{d})^8}{[\sum_{i=1}^{N} (d_i - \bar{d})^2]^4} \]

Where

- \( d_i \) is the amplitude of the \( i \)-th point of the difference signal
- \( \bar{d} \) is the arithmetic mean of the difference signal \( d \)
- \( N \) is the length of the difference signal
Figure 2.6 Signal processing and computation of various fault diagnostic features [8].
2.6 TIME-FREQUENCY ANALYSIS

Not all signals encountered in real life application constitute pure harmonic waveforms. Often transient signals are encountered which results in frequencies that vary over time period of measurement. The DFT is not the best tool to analyze these waveforms due to inherent limitations that produces bias errors and spectral leakage. Even the TSA is helpless for non-stationary signals as the time averaging properties of transient signals change over time. A joint time-frequency analysis is an alternative method to address these limitations. Time-frequency analysis techniques decompose one dimensional time domain signals into a two dimensional plane such that its variation in characteristic frequencies over time can be observed [28,29,30]. The desired properties from the time-frequency distribution function are high clarity, low computational complexity and absence of cross terms so that noise effects are obviated. Short-time Fourier transform (STFT), Wavelet transform, Cohen’s class distributions, Wigner-Ville distribution, Hilbert-Huang transforms etc, are some of the popular tools that fall under the category of time-frequency analysis.

2.6.1 SHORT TIME FOURIER TRANSFORM

The STFT is obtained by windowing the raw time signal into small time signals and applying the Fourier transform on the windowed signals. The primary limitation of STFT is its fixed resolution. The length of the window function dictates the frequency resolution and time resolution, and it is not possible to achieve fine frequency and time resolution simultaneously. A narrow window gives better time resolution, but poorer frequency resolution. On the other hand a wide window gives high frequency resolution but sacrifices time resolution.
2.6.2 WAVELET TRANSFORM

Wavelet transform is similar to STFT, but instead of fixed window size, wavelets use variable sized regions [30]. Often, dilation and translation are applied to the basis functions as it is scaled in width and location. Wavelet transform like any other time-frequency analysis technique promise improved temporal resolution along with frequency information compared to frequency domain analysis. One of the advantages of wavelet transforms is in data compression where the loss of resolution in data is minimized.

\[
STFT\{x(t)\} \equiv X(\tau, \omega) = \int_{-\infty}^{\infty} x(t)w(t - \tau)e^{-j\omega t}dt
\]

Where

- \(x(t)\) is the initial time domain signal
- \(w(t - \tau)\) is the window function
- \(X(\tau, \omega)\) is the Fourier transform of \(x(t)w(t - \tau)\)
- \(\omega\) is the frequency
- \(STFT\{x(t)\}\) is the short time Fourier transform of \(x(t)\)

\[
WT(s, \tau) = \frac{1}{\sqrt{s}} \int x(t)\psi^*\left(\frac{t - \tau}{s}\right)dt
\]

Where

- \(x(t)\) is the initial time domain signal
- \(\psi^*(t)\) is the analyzing wavelet
- \(s(> 0)\) is the scale parameter
- \(\tau\) is the position parameter
2.6.3 WIGNER-VILLE DISTRIBUTION

The Wigner-Ville distribution is a quadratic form time frequency distribution with optimized resolution in time and frequency domains. The WV distribution is obtained by computing the product of the function at past time and future time. The inherent draw back in WV distribution is the presence of interference term, which cause increase noise level. A smoothing technique would reduce the noise problem in WV distribution.

\[ W_x(t, \omega) = \int_{-\infty}^{\infty} x\left(t + \frac{\tau}{2}\right) x^*(t - \frac{\tau}{2}) e^{-j2\pi\omega\tau} d\tau \]

Where
- \( x(t) \) is the initial time domain signal
- \( x^*(t) \) is the conjugate of the time domain signal
- \( X(\tau, \omega) \) is the Fourier transform of \( x(t)w(t - \tau) \)
- \( \omega \) is the frequency
- \( \tau \) is the position parameter

The detailed information about the joint time-frequency analysis techniques, kernel functions are available in literature and books \[\].
3 EXPERIMENTAL PROGRAMME AND TEST FACILITY

The test stand at USC is a full scale AH-64 TRDT test stand with all the actual aircraft hardware that includes the drive train components and the AH-64 vertical stabilizer except for the tail rotor swash plate assembly. The USC TRDT stand is designed to emulate AH-64 tail rotor drive train from the main gearbox tail rotor takeoff to the tail rotor swashplate assembly, as shown in Figure 3.1 and Figure 3.2. The components of AH-64D tail rotor drive train that are subjected to testing at USC CBM test facility are Forward Hanger Bearing (FHB), Aft Hanger Bearing (AHB), Intermediate Gearbox (IGB), and Tail Rotor Gearbox (TGB) [31].

Figure 3.1 Representation of TRDT components tested at USC CBM research center on AH-64D
3.1 TRDT TEST STAND

The multi-shaft drive train consists of four shafts. Three of these shafts lead from main transmission to IGB. These shafts have been assembled to have a misalignment of 2.0 degrees with the help of flexible couplings to simulate the shaft misalignments albeit in safe limits to facilitate study of shaft misalignment influence on radial loads of bearings and drive train vibration. The fourth shaft is installed on vertical stabilizer between TGB and IGB. The test stand configuration, mounting structure, data acquisition systems, and instrumentation comply with military standards. The primary objective of the project is to improve the existing CBM practices of US-Army with minimal change to the equipment that has been in use. The prime mover for the drive train is an 800hp electric (induction) motor controlled by variable frequency drive. The torque loads experienced by the TRDT is achieved by another 800hp electric motor that functions
like a generator to create the braking torque and is controlled by another variable frequency drive. The two motors are each capable of exceeding 150% of the actual loading experienced by the actual aircraft drive train, and they form a regenerative system, thus saving energy. The energy that cannot be regained is due to the loss in power transmission and the losses in electric motors as shown in Figure 3.3. Two universal joints rated for respective loads at input and output end connect the electric motors to the drive train. The hanger bearings support the two equal length long shafts among the four shafts of the TRDT. The hanger bearings are a single row, double sealed, all steel, grease packed ball bearing with a riveted cage. The grease used for hanger bearing lubrication conforms to MIL-PRF-81322 specification.

The Intermediate gearbox is installed at the base of vertical stabilizer. Its function is to reduce the rpm (increase the torque) as well as change the angle of drive. The TGB is a right angled gearbox with a speed reduction ratio of 2.591:1, and is also mounted on the vertical stabilizer, as shown in Figure 3.4. Both the IGB and TGB have spiral bevel gears and are grease lubricated. Typical grease used for TGB and IGB is NS 4405-FG which has Lithium complex as thickener and is of NLGI grade 000. Each gear of TGB and IGB is supported by set of duplex and roller bearings. The tail rotor output shaft passes through the gearbox static mast, designed to take the tail rotor loads. The output shaft is designed to transmit only torque to the tail rotor.

The flexible couplings also assist in hindering the vibration energy transmitted from other components like the hanger bearings and the main transmission. This reduces the signal contamination from the other components of the transmission further providing opportunities for more fundamental understanding of the TGB and the IGB faults and their diagnosis.
Figure 3.3 Schematic layout of AH-64D TRDT test stand at USC and data acquisition

Figure 3.4 AH-64D TRDT test stand at USC CBM research center
The TRDT test stand is a constant speed and dynamic-loading transmission system. The tail rotor drive shafts are run at 101% of the normal operating speed (4863 RPM) throughout the duration of a single test run, while the output motor changes its braking torques to produce specified load conditions, which match flight regimes as requested by the Army Engineering Directorate. Each test run lasts approximately 4 hours and implements the test sequence shown in Table 3.1. It can be observed from the table that the torque is ramped up from 0ft-lb to 1223 ft-lb in the 4 hour test period with intermediate 10 minute cycles where the system is subjected to flat pitch ground loads at 101% of the operating speeds (FPG 101) loads, see Table 3.1. The temperature is measured with a thermocouple close to the gear mesh region in the TGB and near the input bearing for the IGB.

Table 3.1 Loading Profile of AH-64 TRDT test stand [32]

<table>
<thead>
<tr>
<th>Elapsed Run Time (hh:mm)</th>
<th>T/R Drive Shaft #3-4-5 (rpm)</th>
<th>TRGB Output Torque (ft-lb) #</th>
<th>Horsepower (Approx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00 – 00:10</td>
<td>4863</td>
<td>111</td>
<td>30</td>
</tr>
<tr>
<td>00:10 – 01:00</td>
<td>4863</td>
<td>371</td>
<td>100</td>
</tr>
<tr>
<td>01:00 – 01:10</td>
<td>4863</td>
<td>111</td>
<td>30</td>
</tr>
<tr>
<td>01:10 – 02:00</td>
<td>4863</td>
<td>734</td>
<td>198</td>
</tr>
<tr>
<td>02:00 – 02:10</td>
<td>4863</td>
<td>111</td>
<td>30</td>
</tr>
<tr>
<td>02:10 – 03:00</td>
<td>4863</td>
<td>979</td>
<td>264</td>
</tr>
<tr>
<td>03:00 – 03:10</td>
<td>4863</td>
<td>111</td>
<td>30</td>
</tr>
<tr>
<td>03:10 – 04:00</td>
<td>4863</td>
<td>1223</td>
<td>330</td>
</tr>
<tr>
<td>04:00 – 04:10</td>
<td>4863</td>
<td>111</td>
<td>30</td>
</tr>
<tr>
<td>&gt; 04:10</td>
<td>0</td>
<td>0</td>
<td>MSPU</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Downloaded</td>
</tr>
</tbody>
</table>
3.2 INSTRUMENTATION AND DATA ACQUISITION SYSTEM

The TRDT test stand employs two data acquisition systems,

1. IACs-Modernized Signal processing Unit (MSPU), and

2. National Instruments DAQ system.

MSPU is a specialized data acquisition system to measure vibration, and speed, and is designed to be rugged. This is currently installed onboard AH-64 aircraft for those participating in VMEP. It contains high speed data acquisition card, which can accommodate up to 36 accelerometer channels with bandwidth of 1.5 KHz to 96 KHz, eight tachometers, two blade tracker channels, eight general purpose analog or discrete channels, and eight low level analog signals [33]. It has built in self check to test if the sensor is responding to DAQ, and it is built on FPGA architecture optimized for performing filtering, FFT, and other convolution functions. The MSPU also processes this data and computes some diagnostic parameters which have been historically proven to show some insight into machinery health from the vibration data. The PC-GBS software which is also developed by IAC performs information management of the data from MSPU, exports the same to the IMDS-HUMS server, and also computes and displays trends of various CIs over time.

The other data acquisition system is a modular PXI platform from National instruments. This operates in parallel to MSPU, supplements the MSPU as well as acts as redundant DAQ. The NI-DAQ is also configured to collect temperature measurements from electric motors, hanger bearings, and gearboxes besides acquiring electric motors’ torque, and speed. The application end of NI-DAQ is the LabVIEW software [34]. A custom written program processes the data acquired by NI-DAQ which is used for control of the test stand operations, which includes speed, load profile, and handles emergency shutdown in case of excessive vibration, high temperatures, and if high input current is drawn by electric motors.
The experimental data collected for this thesis consists of the discrete vibration time series data acquired every 50 minutes, from the TGB and the IGB by both the DAQ systems. The data is collected from two accelerometers for TGB and one accelerometer for IGB. Each accelerometer has the frequency range of 0 to 96 KHz. There are currently, two types of accelerometers that are installed on TRDT: Bracket type and Spark-plug type. All the accelerometers are sampled at 48 KHz which is what MSPU does on onboard aircraft.

A tachometer installed on the input shaft is used for computing the shaft synchronous signal. The thermocouples were installed close to the input duplex bearing and the output roller bearing for the TGB as shown in Figure 3.5. Another thermocouple for article 3 was inserted less than 0.5 inches above the input gear surface through a specially modified service plug. A thermocouple and an accelerometer were also installed on IGB near input duplex bearing as shown in Figure 3.6. The details about the sensors, their location on TRDT and their affiliation with the respective DAQ is presented in Table 3.2.
Figure 3.5 Accelerometer and Thermocouple locations on TGB
Figure 3.6 Accelerometers and Thermocouples location on IGB
### Table 3.2 Sensors details

<table>
<thead>
<tr>
<th>Location</th>
<th>Number</th>
<th>Sensor type</th>
<th>Corresponding DAQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHB</td>
<td>2</td>
<td>Accelerometer bracket type</td>
<td>MSPU and NI-DAQ, 1 each</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>K type Thermocouple</td>
<td>NI-DAQ</td>
</tr>
<tr>
<td>FHB</td>
<td>2</td>
<td>Accelerometer bracket type</td>
<td>MSPU and NI-DAQ, 1 each</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>K type Thermocouple</td>
<td>NI-DAQ</td>
</tr>
<tr>
<td>IGB</td>
<td>3</td>
<td>Spark plug type</td>
<td>2 are connected to MSPU, 1 to NI-DAQ</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>K type Thermocouple</td>
<td>NI-DAQ</td>
</tr>
<tr>
<td>TGB</td>
<td>2</td>
<td>Spark plug type</td>
<td>MSPU and DAQ, 1 each</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>K type Thermocouple</td>
<td>NI-DAQ</td>
</tr>
<tr>
<td>Input Shaft end</td>
<td>1</td>
<td>Tachometer</td>
<td>MSPU</td>
</tr>
</tbody>
</table>
3.3 EXPERIMENT

The experiment involves testing three different TGBs that are lubricated as specified in the beginning of the test and are gradually drained as the test progresses such that almost all the lubricant is drained out of the gearbox after few test runs except for the residual lubricant film on the gear teeth and casing. This is accomplished by puncturing the outboard seal near the end of static mast, see Figure 3.7.

Figure 3.7 TGB assembly cross section showing various sub-components[1]

The grease leakage from TGB of an Apache AH-64 has been one of the most common problem that have initiated emergency grounding and maintenance actions, thus hurting the mission at hand. The aim of the test plan was to measure the remaining useful life and record the vibration signatures that would aid as symptoms in case similar situation arises during operations. The objective of this thesis is to evaluate currently used CIs, and develop an algorithm/model or an alternative condition indicator that can supplement the existing set of condition indicators, all in an effort to facilitate early detection of faults. It is very crucial to understand the physics and
root causes that lead to the failure to define a better CI. The approach is to investigate the vibration signatures prior to the failure, and compare with the baseline vibration signatures as well as plotting the trends of various existing and prospective CIs. The current study is part of the test plan that was devised by AED and USC CBM research facility to simulate a worst-case scenario for the two ball bearings that support the TGB output shaft assembly by allowing grease to leak through the output seal from the static mast. To accomplish this, output seal’s gasket was cut at the bottom, and 0.5 inch of the material is removed. Furthermore, the retaining hoop spring that assists in sealant function is also eliminated. Three such TGBs are tested without changing the IGB, the shafts in the TRDT, and the components that couple to the output section of the TGB so that their health does not influence the data collected.

Figure 3.8 seeding procedure utilized to induce an output seal leak [1]
4 EXPERIMENTAL RESULTS AND EVALUATION OF CURRENT CONDITION INDICATORS

The important objective of VMEP program is to detect the faults with sufficient lead time. The current VMEP algorithms implemented on the PC-GBS at USC test stand are listed in Table 4.1. The PC-GBS on real aircraft includes various other CIs that monitor the health of the Nose gearbox, hanger bearings etc, but in the Table 4.1 only those CIs that are relevant to health of TGB and IGB are listed. The FM4, SLF, SI and CF are expected to indicate localized gear fault, and the DA1, DA2, DA3, ER are believed to yield information about heavy gear wear. All the CIs mentioned in Table 4.1 have been evaluated for the surveys collected after the 1223 ft-lb load cycle from the experimental data generated for the articles mentioned in section 3.3.

Table 4.1 Condition indicator algorithms implemented in USC TRDT test stand by MSPU

<table>
<thead>
<tr>
<th>Algorithm Name</th>
<th>Caution Limit</th>
<th>Exceedance Limit</th>
<th>Algorithm Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 FM0</td>
<td>100</td>
<td>200</td>
<td>FM0-Figure of Merit 0. It is the peak level of the synchronous signal average divided by the RMS average</td>
</tr>
<tr>
<td>2 FM4</td>
<td>5</td>
<td>8</td>
<td>FM4- Figure of Merit 4. It is the normalized kurtosis of the signal average</td>
</tr>
<tr>
<td>3 DA1</td>
<td>100</td>
<td>200</td>
<td>DA1-Diagnostic Algorithm 1. It is the RMS of the signal average</td>
</tr>
<tr>
<td>4 DA2</td>
<td>100</td>
<td>200</td>
<td>DA2- Diagnostic Algorithm 2. It is the RMS of Residual signal</td>
</tr>
<tr>
<td>5 DA3</td>
<td>100</td>
<td>200</td>
<td>DA3 – Diagnostic Algorithm 3. It is the ratio of peak of envelope divided by RMS of the mesh</td>
</tr>
<tr>
<td>6 Calculate AFD data</td>
<td></td>
<td></td>
<td>Calculates an asynchronous frequency domain spectra</td>
</tr>
<tr>
<td>7 Calculate peak-peak</td>
<td></td>
<td></td>
<td>Finds a peak in the AFD with or without a tachometer</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>AM Demod</td>
<td>Performs an amplitude demodulation</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Modulation Ratio</td>
<td>Calculates the modulation ratio</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Synchronous time average</td>
<td>Calculates the synchronous time average waveform with a fixed size window defined by the synchronous frequency</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>CF</td>
<td>10 20</td>
<td>CF-Crest Factor. It is the ratio of synchronous average peak amplitude to its RMS level</td>
</tr>
<tr>
<td>12</td>
<td>ER</td>
<td>100 200</td>
<td>ER-Energy Ratio. It is the standard deviation of difference signal divided by standard deviation of regular signal</td>
</tr>
<tr>
<td>13</td>
<td>SLF</td>
<td>5 8</td>
<td>SLF-Sideband Level Factor. It is obtained by computing the amplitude of 1R sidebands divided by standard deviation</td>
</tr>
<tr>
<td>14</td>
<td>SI</td>
<td>100 200</td>
<td>SI-Sideband Index. Computed by performing the ratio of Sum of largest nR sidebands to the number of sidebands</td>
</tr>
</tbody>
</table>

4.1 TGB ARTICLE 1

The article 1 has been tested for total of 485.5 hours with the load profile mentioned in Table 3.1, and data acquisition was performed according to the test plan mentioned in Chapter 0. The article was serviced with grease before starting the run. As expected, large volumes of the grease had effused out of the static mast within first 150 hours of testing. The gearbox inspection after approximately 260 hours revealed that the gearbox main compartment was underserviced. The gearbox was serviced with grease and the testing was resumed to repeat the scenario of lubricant starvation. The article-1 was discontinued from testing when the temperatures reached 315°F. The auto-power spectrum of the TGB from the beginning of the run to the end of the run reveals an increase in gear mesh fundamental frequency amplitudes from 2.5g to approximately 4g, see Figure 4.1 and Figure 4.2. Further from the auto-power spectrum plots it can be seen that the second and third harmonics of gear mesh have shown an increase in their amplitudes by three folds. This suggests that there could be significant damage to meshing teeth. An inspection with boroscope revealed heavy wear on the input gear of TGB, refer Figure 4.3.
Figure 4.1 Auto power spectrum of TGB article 1 in the initial phase of testing

Figure 4.2 Auto power spectrum of TGB article 1 in the final phase of testing
Figure 4.3 TGB article 1, borescopic pictures revealing heavy wear on the input gear of TGB [1]

Except for the frequency domain plots which indicated increase in gear mesh harmonics amplitudes, none of the CIs have crossed exceedance limit, refer threshold limits in Table 4.1. The TGB Lateral Bearing Energy, and TGB vertical Bearing Energy condition indicators have crossed the caution limit refer Figure 4.4 and Figure 4.5. The Time axis on the plots for CIs consists of samples acquired at discrete time intervals at FPG 101 load after 1223 ft-lb load cycle. Since these samples have been distributed over multiple hours and days, the actual numbers are not represented on the scale for brevity.
Figure 4.4 TGB article 1, Lateral Bearing Energy CI across time towards the end of the run showing caution limit

Figure 4.5 TGB Article 1, Vertical bearing energy CI after the cut seal towards the end of the run
Nevertheless the input, and the output gears’ DA1 (see Figure 4.6) and DA3 (see Figure 4.10) have shown a sharp increase in their magnitude towards the final 50 hours, indicating an increase in total vibrational energy which was also evident in the power spectrum plots. A slight increase in sideband activity was observed from the SI (see Figure 4.8) but observing their threshold limits (see Table 4.1) the variation can be considered as negligible. From the borescope pictures, it was observed that there was heavy wear on the gear teeth, but the FM0, and the ER CIs (see Figure 4.9) did not indicate any alarming variation. There was no noticeable damage that was concentrated on single tooth of either input or output. Hence the insignificant variation in FM4 (see Figure 4.7) was as expected. This can be further confirmed from low variation in Crest Factor CI.

Figure 4.6 TGB article 1, change in DA1, and DA2 over the whole period of testing
Figure 4.7 TGB article 1, Figure of Merit group CIs for input 22T and output 57T gears over the whole period of testing

Figure 4.8 TGB article 1, input and output gears’ sidebands based CIs variation over duration of testing
Figure 4.9  TGB article 1, input and output gears’ energy ratio based CIs variation over duration of testing

Figure 4.10  TGB article 1, input and output gears’ DA3 variation over the duration of testing
4.2 TGB ARTICLE 2

The TGB article-2 has been serviced only at the initial stage of the experiment, after seeding the fault on the TGB. During operation the lubricant was bled out of the static mast from the punctured output seal. The boroscope pictures collected from TGB after 300 hours indicated noticeable tooth wear, but the testing was continued. The testing on this article was terminated after 500 hours when it was identified that one of the tooth on the input gear chipped and an adjacent tooth suffered damage on its crest towards the corner. An interesting thing to note is that there were no obvious thermal indicators for this incident. An inspection with boroscope revealed heavy wear on the input gear of TGB, and one of the teeth was observed to have been chipped, refer Figure 4.11. The power spectrum of the TGB from the beginning of the run to the data acquired prior to tooth breakage reveals an increase in gear mesh second harmonic from 4g to 22.4 g, refer Figure 4.12 and Figure 4.13. A heavy wear on the tooth surface lives possibilities for sub-surface fatigue cracks that could have been responsible for the tooth breakage.
Figure 4.11 TGB Article 2, input gear after one of its tooth broken and the other tooth addendum was also damaged [1]
Figure 4.12 Auto power spectrum of TGB article 2, in the initial phase of experiment

Figure 4.13 Auto power spectrum of the TGB article 2, prior to failure

For the second TGB article, none of the CIs directly related to TGB have even crossed the caution limit. The TGB Vertical Bearing CI was close to reaching the caution limit towards the end of the run, see Figure 4.14. The DA1, for the input and output gear has shown strong change in its magnitude in the final phase prior to failure. Also, the SI for the input gear, which measures the mean energy of the largest sidebands, had an observable increase in its value. The surprise element here is the FM4, that was supposed to indicate individual tooth damage did not create an alarm and its value was close to 3 which would be observed for Gaussian noise, refer

Figure 4.14 TGB article 2, Lateral Bearing energy CI across time, towards the final phase before failure
There were multiple occasions of small spikes in FM0 and quite sharp spike in input gear DA3 CI. Nevertheless the DA3 CI’s threshold limit was 200 which is far from the peak amplitude of the DA3 during the whole test period. The ER, CF, DA2 CIs have not shown much utility for the TGB article 2.

![Figure 4.14 TGB article 2, Lateral Bearing energy CI across time, towards the final phase before failure](image-url)

Figure 4.14 TGB article 2, Lateral Bearing energy CI across time, towards the final phase before failure
Figure 4.15 TGB article 2, change in DA1, and DA2 over the whole period of testing

Figure 4.16 TGB article 2, Figure of Merit group CIs for input 22T and output 57T gears over the whole period of testing
Figure 4.17 TGB article 2, input and output gears’ sidebands based CIs variation over duration of testing

Figure 4.18 TGB article 2, input and output gears’ energy ratio based CIs variation over duration of testing
4.3 TGB ARTICLE 3

For the TGB article 3, a baseline experiment was conducted without bleeding the lubricant for first 68 hours, and later the lubricant was bled from the TGB as described in the previous chapter. After 534 run hours, the gearbox core temperatures have reached 300F. The borescope images indicated an increase in tooth surface wear on the input gear. Similar surges in temperature were observed after 569 run hours, but the experiment was resumed after halting the test till the temperatures subsided. The test was terminated at the end of 675 hours due to surge in TGB temperature to 325F. This gearbox has registered a little more than 600 hours even after the baseline experiment duration is discounted for comparing it with the other two gearboxes. Interestingly, the inspection of the tooth surface (see Figure 4.20) towards the end of the run neither showed signs of heavy wear as in TGB article 1 nor any individual tooth defects as in TGB article 2. The auto-power spectrum of the TGB article 3 shows significant increase in gear mesh second harmonic amplitudes from 4.5g to 14g, see Figure 4.21 and Figure 4.22. Also, from the power spectrum towards the end of the run, sidebands amplitudes of gear mesh third harmonic

Figure 4.19 TGB article 2, input and output gears’ DA3 variation over the duration of testing
have increased. For the current article, the output gear FM4 CI was hovering just above caution limit for the surveys collected after 1223 ft-lb, right from its installation, see Figure 4.25. The only CI that has shown an increase in its value was DA1, but the values were an order less than the threshold limit, Figure 4.24. There was an increase in FM0, and SI CIs on multiple occasions for both input and output gear, see Figure 4.26. But the relative increase in SI and FM0 CIs are insignificant to create an alarm. Similar pattern was observed with input gear SI and SLF CIs. Here as well the ER and CF CIs have not shown any utility, Figure 4.27.

Figure 4.20 TGB article 3, borescope pictures after the final phase of testing [1]
Figure 4.21 Auto power spectrum of TGB article 3, during initial phase of testing

Figure 4.22 Auto power spectrum of TGB article 3 prior to the end of testing
Figure 4.23  TGB article 2, Lateral Bearing energy CI across time, towards the final phase before failure

Figure 4.24 TGB article 3, change in DA1, and DA2 over the whole period of testing
Figure 4.25 TGB article 3, Figure of Merit group CIs for input 22T and output 57T gears over the whole period of testing.

Figure 4.26 TGB article3, input and output gears' sideband analysis based CIs.
Figure 4.27 TGB article 3, input and output gears’ energy ratio based CIs variation over duration of testing

Figure 4.28 TGB article 3, input and output gears’ DA3 variation over the duration of testing
From the experiments on all the three articles of the TGB, it can be observed that even though the defects were observed on the gear tooth surface, the bearing CIs have been more successful in climbing to the caution limits. This could be due to the impact energy from the gear mesh being transferred to the bearings in the gearbox, but not necessarily a fault with the bearing itself. This inference can be supported by the increase in gear mesh harmonics observed in auto-power spectrum plots during final phases of the experiment compared to the initial phases. This indicates that in spite of having quite a number of CIs which measure different phenomenon like differences in raw time signal, difference signal, residual signal, time synchronous averaged signal, etc., the condition monitoring objectives have not been successfully met for the effort that was devoted. This suggests an alternative CI which can either improve the efficacy of condition monitoring or produce approximately same results as the current CIs with relatively lower computing power could be beneficial.
5 ASYNCHRONOUS TO SYNCHRONOUS ENERGY RATIO IN TIME DOMAIN

Most of the CIs currently implemented for gear condition monitoring either directly or indirectly require the frequency spectrum information which is most often computed with the DFT. Typical CIs that are directly based on the DFTs are the Modulation Ratio, the AM demodulation, SLF, and SI, as they require information about gear mesh harmonics and its sidebands. On the other hand DA2, ER, FM4, NA4, FM4*, NA4* either use the residual signal or the difference signal whose computation also involves awareness about mesh harmonics and sidebands.

As part of the research pursued, a simple condition indicator is proposed in this thesis. The proposed CI is based on just time series signal and has produced similar results as some of the current condition monitoring algorithms with relatively lower computational expense. It also has ability to offset disadvantages that are encountered when time series signal is transformed into frequency domain using Fourier transform.

One of the major disadvantages of the Discrete Fourier transforms is the spectral leakage, which occurs when the signal is neither completely transient nor completely periodic. In these circumstances computation of DFT from the time signal leaks energy into other frequencies which are not representative of the actual signal, refer Figure 5.1. These types of signals are encountered often when there is any breakage of surface ridges during meshing on the mating gear tooth surfaces, etc. In general, windowing techniques are employed to minimize the spectral leakage errors. The windowing techniques force the signal to appear transient within the time
period. But often when a proper windowing technique is not selected then the leakage errors still persist. Windowing techniques hamper the quality of periodic signals when they force to become transient.

![Figure 5.1](image)

Figure 5.1 Generic non-periodic sample set that could create spectral leakage

Even though Implementation of DFT using Fast Fourier transform (FFT) has been popular, it is applicable only when the number of samples is a value which is an exponent of 2. Most often this is achieved by either truncating the time series data where the valuable information is not effectively utilized or padding the sample with zeroes which marginally increases computational expense. Furthermore, the resolution of frequencies in frequency analysis as well as joint time frequency analysis is always a tradeoff with respect to the computational expense. Hence, a time series based CI would not only use all the samples collected, but also is easier for implementation on real time condition monitoring system.

The proposed CI is based on the energy of the asynchronous time domain signal and the time domain signal averaged with respect to the synchronous frequency of interest. Hence this CI is named as Asynchronous to Synchronous Energy ratio of Time (ASET) domain signal.

For the implementation of ASET, it is assumed that the noise present in the signal follows Gaussian distribution (see Figure 5.2), and has its mean and variance constant throughout the
experiment. The assumption is not far from the reality as vibration signals from the rotating systems are expected to have a mean value equal to zero. If the mean is different from zero, it can be corrected by shifting the signal. Also, if the white noise has changing mean or variance, most of the conventional metrics that are currently implemented could provide ambiguous information.

Figure 5.2 Distribution of Gaussian noise[11]

5.1 ASET DEFINITION

It is well known fact, that root mean square (RMS) value of a signal is directly proportional to energy of the signal. Hence ASET is defined in terms of the RMS values of the respective time domain signals.

\[
ASET = \frac{\text{RMS(Asynchronous Time Signal)}}{\text{RMS(Time Synchronous Averaged signal)}}
\]

ASET is expected to be greater than one as the asynchronous time signal consists of all the frequencies and noise that are not represented in the TSA signal.

For TGB, the input gear (pinion) has 22 teeth and the output gear has 57 teeth. The synchronous frequency for computing TSA of input and output gears are the frequencies of their
rotations respectively. Accordingly there exists two ASET CIs for the input and output gears of the TGB. They are expressed as follows:

\[
ASET_{22T} = \frac{RMS(Asynchronous \ Time \ Signal)}{RMS(Time \ Synchronous \ Averaged \ signal \ with \ respect \ to \ 22 \ teeth \ gear)}
\]

\[
ASET_{57T} = \frac{RMS(Asynchronous \ Time \ Signal)}{RMS(Time \ Synchronous \ Averaged \ signal \ with \ respect \ to \ 57 \ teeth \ gear)}
\]

Similarly for IGB two ASET CIs can be defined. They are:

\[
ASET_{37T} = \frac{RMS(Asynchronous \ Time \ Signal)}{RMS(Time \ Synchronous \ Averaged \ signal \ with \ respect \ to \ 37 \ teeth \ gear)}
\]

\[
ASET_{49T} = \frac{RMS(Asynchronous \ Time \ Signal)}{RMS(Time \ Synchronous \ Averaged \ signal \ with \ respect \ to \ 49 \ teeth \ gear)}
\]

The proposed signals are technically energy ratios, but are not similar to the energy ratio CI. In the ER CI the ratio of energies of difference signal and residual signals is computed. This involves computation of DFTs to identify harmonics and sidebands, followed by removal of these frequencies, and computation of inverse DFT to produce residual and difference signals. To the best of author’s knowledge, in all the existing CIs, there was no proposal to make utilization of both asynchronous time domain and synchronous time domain signals simultaneously and address the anomaly identification.

The condition of the component is indicated by monitoring the trends in ASET based CIs. ASET CIs provide qualitative perspective that indicates presence of anomaly in vibration signatures.
5.1.1 CASE 1: ASET INCREASES WITH RESPECT TO PREVIOUS STATE POINTS.

An increase in ASET with respect to previous state points could imply

1. Presence of transient and periodic events in the duration of measurement. This results in increase of asynchronous time domain signal energy only. Hence the net ratio increases.

2. Modulation of synchronous frequencies. This results in shifting of the energy from the synchronous frequencies to the sidebands. In this case, the energy in time synchronous averaged signal is expected to decrease as the sideband frequency is not necessarily an integral multiple of synchronous signal. Hence the net ratio increases.

3. Reductions in gear mesh amplitudes or the amplitudes of any other synchronous frequency. This would result in decrease of energy of both the asynchronous and the TSA signal, but the contribution of gear mesh amplitudes to the TSA is higher. Hence this results in decrease of ASET.

4. Refer to point 1 in case 2.

5.1.2 CASE 2: ASET DECREASES WITH RESPECT TO PREVIOUS STATE POINTS

A decrease in ASET with respect to previous state points could imply

1. This could be an indication of increase in gear mesh amplitudes or wear of the shaft, damage to the inner race of the bearing that is supporting the gear shaft etc. Both the gear mesh amplitudes and the damage of the inner race of the bearing, or damage to the gear shaft should be evident as an order of the synchronous signal. This is manifested as increase in energy of the TSA signal and asynchronous signal as well.
But since the TSA signal is composed of only synchronous frequencies, the relative contribution of the gear mesh frequencies is higher to TSA compared to asynchronous signal. Hence there would be a net decrease in the ASET. Incidentally, this would also result in increase of ASET for input gear, but decrease in ASET for output gear when the damage is on the output gear and vice versa. The ASET for input and output gear not only provides information about the respective gears but comparing them against each other reveals information about the damage to non-meshing surfaces of input and output gears (e.g. shaft supporting gears, inner race of bearings supporting these shafts).

2. Another very unlikely case is a foreign signal that happens to have frequency which is an order of the synchronous frequency. Even in this case both TSA and asynchronous signal energy increases but the relative increase in TSA is expected to be higher compared to asynchronous time signal.

The proposed CI, ASET algorithm has been applied on the vibration signals obtained for the TGB article 2 and 3, and the IGB that was in the transmission line when the experiments on the TGB were performed. The TGB article 1 was not used for analysis with the proposed CI, as the article 1 has been serviced with lubrication once during the experiment phase and this renders the article 1 to have different experimental conditions compared to the other two TGBs.

The results of the computation of ASET condition indicator for all the three gearboxes are presented in this section. Further, ASET CI has been compared with the current condition indicators to reveal relationships with respect to existing CIs. The intention of the current study was not to derive the functional relationship that exists between ASET and other CIs, rather to provide a qualitative perspective that indicates the ASET is not some random mathematical function, but has potential to identify anomaly from time domain data alone. This approach has
been adopted with the IGB article, TGB article 2 and TGB article 3 for comparing ASET with existing CIs.

5.2 IGB ARTICLE

Figure 5.3 Comparison of ASET of input 37T and output 49T gears' of IGB test article

From the Figure 5.3, it is interesting to note that the ASET for the input and output gear share a similar trend and magnitude. This indicates that there was no obvious damage to the input and output gear shafts’ bearings. Comparison of the ASET CIs of input and output gears with a linear functional relation between FM0 and FM4 CIs show similar trends, see Figure 5.4 and Figure 5.5. The linear relationship was arbitrarily chosen to scale the variation in the functional relationship to facilitate effective comparison with the proposed CI.
Figure 5.4 IGB article, Comparison of ASET of input gear with linear combination of FM0, FM4 CIs of input gear

Figure 5.5 IGB article, Comparison of ASET of output gear with linear combination of FM0, FM4 CIs of output gear
Figure 5.6 ASET ratios for input 22T gear, output 57T gear over the whole duration of experiment

The Figure 5.6 presents the ASET ratio computed for input and output gear of the TGB article which has the broken tooth. An increase in ASET ratio could be attributed to increase in other frequencies which are not synchronous with the gear speed which includes the frequencies that arise due to meshing when there is heavy wear as well as side banding. From the figure it can be observed that the output gear has higher ASET ratio compared to input gear which is an indication that there is more energy in the input gear TSA signal compared to output gear TSA signal. This confirms the common notion that the gear with lower number of teeth has higher rotational frequency which results in accelerated wear.

If this trend is compared with the conventional CIs, it can be inferred that this variation is almost similar to the variation in FM0 of both input and output gears almost till the two thirds of the experiment duration and then it deviates. If FM0 is considered as reliable, then it suggests that there has been instances of wear progressing which causes intermediate phases of roughening of
the contact surface, followed by smoothening due to grinding effect and inception of rough surface again. The deviation in ASET can be explained as the increase in gear mesh amplitudes or once per revolution amplitudes, this can be further justified by the evidence of the broken tooth found in the gear box towards the end. The RMS value of the raw signal further hints that these conclusions are arguably right.

Figure 5.7 Comparison of ASET input gear with a linear combination of FM0, FM4 CIs of input gear
Figure 5.8 Comparison of ASET of output gear with a linear combination of FM0, FM4 CIs of output gear
5.4 TGB ARTICLE 3

Figure 5.9 Comparison of ASET ratios for input and output gear for the whole duration of experiment

From the Figure 5.9, it can be observed that both the input and output gear have almost similar ASET ratio in the early period of testing, which is an indicative of uniform meshing of both participating gears. As mentioned in section 4.3, for the TGB article 3, baseline experiments were conducted without seeding the output seal fault. Hence the lubricant did not drain out of TGB. The ASET ratio for input and output when plotted together suggests this without ambiguity. After the baseline testing period, a fault was seeded by puncturing the output seal and the lubricant has been drained out of TGB. Here onwards the gear teeth were starved of lubricant and the wear could have accelerated. As it was mentioned in previous section, the gear with fewer teeth suffers higher wear which is indicated by lower ASET magnitude for input gear. This trend represented by ASET for input and output gear of TGB, when compared with the trends of FM0, FM4 of input and output gear suggests that the proposed CI shares a linear functional relationship with FM0, FM4, albeit with unequal non-normalized weights. This can be further confirmed by
observing that all the peaks in both FM0 and FM4 CI contribute to the ASET, see Figure 5.10 and Figure 5.11. The plots have been generated after scaling the CIs such that it is easier to compare the proposed CI with the parameter of interest. As mentioned the purpose of this research study was not to identify a functional relationship of ASET with other CIs, but to qualitatively describe ASET behavior and confirm with the variations in existing CIs. Another reason for not emphasizing on deriving a functional relationship of ASET with other CIs, is that they are dimensionally not equivalent and there could be some other phenomenon captured by ASET but is not represented by existing CIs, hence the scope of ASET is left for exploration.

Figure 5.10 Comparison of ASET of input gear with linear combination of FM0 and FM4 CIs of input gear
Figure 5.11 Comparison of ASET of output gear with linear combination of FM0, FM4 condition indicators of output gear

The evaluation of ASET for the two TGB test articles, and the IGB, and its comparison with the conventional CIs suggests that the ASET exhibits some functional relationship with FM0, FM4 but with non-equal, non-normalized weights which are not known as the intention of the current research is not to derive a functional relationship among these CIs. Besides the deviation in the proposed CI and the conventional CIs towards the end of the run indicate that there exists some other parameter which is constant till the final phases and changes (preferably decreasing) until the damage has progressed to alarming levels.
6  CONCLUSIONS

In the proposed research three different gearboxes have been subjected to one of the worst-case scenario for TGB, and IGB which is lubricant starvation. The CIs that are expected to identify the impending failure have been evaluated. The current research has demonstrated the inadequacy of current condition indicators derived from vibration analysis for a specific case of one of the possible worst case scenarios that could be experienced by a gearbox. Since, the TGB grease leakage has been one of the common problems encountered, it is desired to have a CI to provide a warning as early as possible as this is critical for implementation of CBM objectives of US Army for AH-64 fleet. The TGB Lat bearing energy CI has been the most effective CI in identifying the problem in advance, but the time between the warning and failure was not sufficient. Nevertheless it proved to be a reliable condition indicator. From the experimental data it was observed that the DA3 has been one of the CIs which have shown a sharp increase in final stages as the damage was progressing. The CIs that have shown significant difference with respect to previous state points are SI, DA3, and FM0 CIs.

The other CIs like Crest Factor, FM4, DA2, have neither crossed thresholds nor provided an alarming variation in its value. The energy ratio CI involves computation of difference signal, and residual signal which also involves forward DFT, identifying harmonics and sidebands, eliminating all or some of them from the signal as required and performing inverse DFT. Despite all this computational effort the ER did not prove to be effective. From the inferences based on evaluation of condition indicators for the current experiment, the thresholds for the CIs seem to have very high caution and exceedance limit. Perhaps the CI thresholds need to be updated to
some value lower than existing limits. Or instead of considering the magnitudes as a CI, it could be useful to assess the rate of change of the CIs as well in evaluating the health of the component. Also, a generalized model that dynamically updates threshold would be an ideal solution as every component is unique and its health preferably has to be measured with respect to its time history rather than wait for some threshold value set by observing the means of few test components [35].

Almost all the CIs defined currently for vibration data either directly or indirectly depend on discrete Fourier transforms. Hence they inherit the major limitations of DFT, which includes spectral leakage, inability to process a transient event along with periodic variations. In this thesis an alternative CI, named ASET that is based on only time domain signal is defined.

The reason for defining the CI based on time domain signal alone without transforming into frequency domain is to offset the limitations of DFTs. Also, eliminating the need for requirement of DFTs enables the ASET condition indicator to look for the transient variations in the otherwise periodic signals measured during data acquisition. Hence the proposed CI is capable of dealing with the transient events such as tooth crack formation and crack growth if the acquisition has been performed in this period unlike the CIs that depend on DFT.

The thesis presents the definition of ASET and hypothesizes its expected behavior. The ASET CI is expected to react to change in gear mesh amplitudes, transient events and any modulation phenomenon in the vibration signal. The implementation of the ASET algorithm on the experimental data revealed the trends that are hypothesized. Further comparison with FM0, FM4 and SI CIs, indicated that the ASET reacts to heavy wear and localized wear without having to perform cumbersome computation of normalized kurtosis as in FM4 or performing forward Fourier transform, identifying sidebands and computing SI. The thesis presents the relation of ASET with respective to other CIs from a qualitative perspective as the ASET is not just a linear function defined based on all the existing CIs as its independent parameters. Further, the
qualitative treatments leaves ASET scope open for including any other component anomalies. The ASET CI also has ability to indicate the failures on the bearing inner race, gear shaft and localize to a particular gear in mechanical relationship.

The proposed CI reacts to multiple failure modes with lower computational burden unlike some of the currently implemented CIs and hence has potential to substitute some of the existing CIs. The ASET CI can be an alternative diagnostic algorithm that provides information about sidebands, gear mesh amplitudes from just the time-domain data. For future investigations, it would be interesting to assess the ASET behavior for epicyclic gear trains. Perhaps it could localize the anomalies as the epicyclic gear trains involve multiple ASET ratios.
REFERENCES


[6] "Analysis of Benefits Associated with Army Aviation Condition Based Maintenance (CBM)".


Machinery Diagnostics (I) Introduction to the Wigner-Ville Distribution


[33] IAC 1209 Modernized Signal Processing Unit. [Online]. www.iac-online.com

[34] National Instruments LabVIEW Software. [Online]. www.labview.com


[47] P. J. Dempsey, M. Mosher, and E. M. Huff, "Threshold Assessment of Gear Diagnostic Tools on the


