QATAR UNIVERSITY

COLLEGE OF ENGINEERING

EXPERIMENTAL DETECTION OF LOCALIZED SURFACE DEFECTS IN BALL BEARINGS USING VIBRATION ANALYSIS

BY

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A Thesis Submitted to
the Faculty of the College of
Engineering
in Partial Fulfillment
of the Requirements
for the Degree of
Masters of Science in Mechanical Engineering

January 2018

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ABSTRACT

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Title: Experimental Detection of Localized Surface Defects in Ball Bearings Using Vibration Analysis

Supervisor of Thesis: Sadok, Sassi.

Bearings play a crucial role in the functioning of rotating machinery. Any failure of this critical component may cause severe disturbance to production and can lead to human injures. Condition Monitoring tools are needed to assure the healthy state of rolling element bearings during the operation. This study aimed at the monitoring of bearing health condition, based on vibration measurement. For that purpose, an appropriate test rig was designed, manufactured and tuned to accommodate the test bearings. In particular, an innovative solution for rapid mounting and dismounting of bearings on the supporting shaft was tested and used successfully in the first phase. In a second phase, tiny circular defects were seeded on outer and inner rings of similar bearings, by using the principle of Electro-Discharge Machining. The defects sizes in this investigation ranged from 0.35 mm up to 3 mm. All tested bearings had the same testing conditions. In the last phase of the project, a healthy bearing (without any defect) was installed on the test rig, and vibration measurements were taken to serve as reference data later. Each damaged bearing was installed on the test rig, and vibration measurements were performed again. Several MATLAB codes were used for recording and analyzing the experimental data. The results obtained from this work clearly show that different parameters could be extracted from time domain and frequency domain. These parameters were found to be sensitive to the growth of defects sizes in different extent, which allows the assessment of bearing health condition. In time domain, the most sensitive parameters were found to be the kurtosis and the peak amplitude. In addition to the conventional time-domain parameters, which are commonly used by vibration practitioners, two new time-domain parameters were introduced for the first time in this research. They were named as SIANA and INTHAR. Both of them demonstrated high sensitivity to the detection of growth in bearing defects sizes. In the frequency domain, the second and third harmonics of ball pass frequencies on inner and outer rings were found to be the most sensitive parameters. In general, the indicators extracted from the frequency domain seem to be more sensitive than time domain parameters to the evolution of degradation inside the bearing. The Envelope Detection (ED) was also used in this study as a possible technique to track the increase of damage extent inside bearings. Compared with direct spectrum, this approach allowed for better visualization of BPFO and BPFI. Furthermore, the use of ED was found to filter the electrical frequencies on the signal, which were hiding the real signature of defects.

DEDICATION

"I dedicate this work to my beloved wife Mariam, for her faithful support and patience during the completion of this thesis.

I would also like to express my deepest gratitude to my parents for their prayers and motivation as well as my brothers and sisters for their support"

ACKNOWLEDGMENTS

First of all, all thanks and praises are for Allah Subhana-wa-ta-allah for giving me strength and patience for fulfilling this project.

The work presented below was carried out at the Mechanical and Industrial Department of Qatar University. I would like to express my deep gratitude to the university and the faculty members who supported the project by their valuable ideas and assistance, especially to my supervisor Dr. Sadok Sassi, whose immense contribution enabled the successful completion of this project.

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CHAPTER 1 INTRODUCTION

1.1 What is Bearing?

In today’s world, one can encounter the rolling and spinning elements incorporated in a huge range of subjects for everyday use, starting from the skate or car wheels finished with electric motors, microwave tables and even personal computers. One small bearing makes the core principle of performace for most of today’s machines in real life. Without bearings it would be almost impossible to manufacture items with precision in a massive scale. Moreover, without bearings the parts of the devices would wear out rapidly due to excessive friction.

The bearing belongs to one of the key components in any rotating machine. It allows relative motion between moving parts, reduce friction and wear, and has good load caring capacity. A common rolling-elements bearing consists of a number of rolling elements incorporated between an inner and an outer ring. Both rings have grooves or raceways to guide the rolling elements. A cage is used to separate the rolling elements from each other as shown in Figure 1.

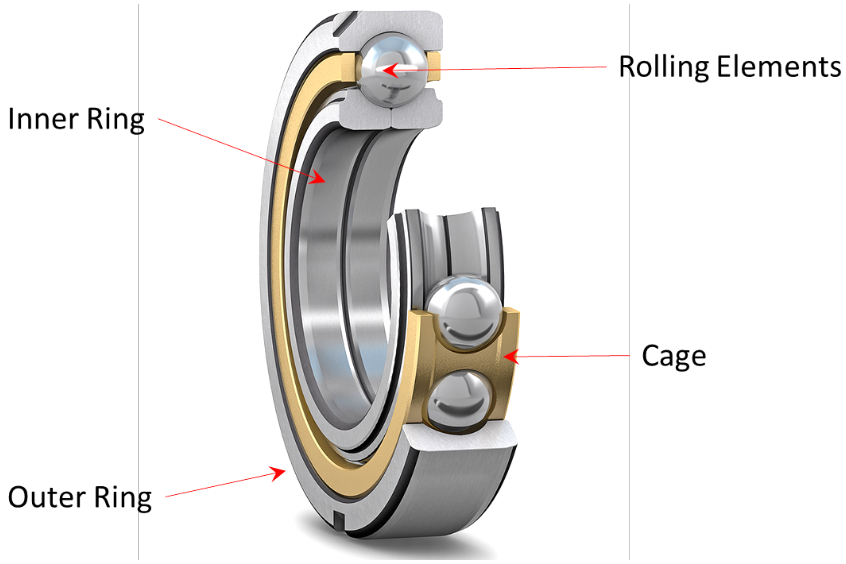


Figure 1: Composition of a ball bearing

1.2 The History of Bearing

The concept of bearings dates back to 2400 BC in Old Egypt when the “pharaohs” used "rolling bodies" such as the round timbers to build the pyramids Figure 2. With rolling bodies, the speed of displacement was increased, the friction problems were reduced and the tasks were made less difficult.

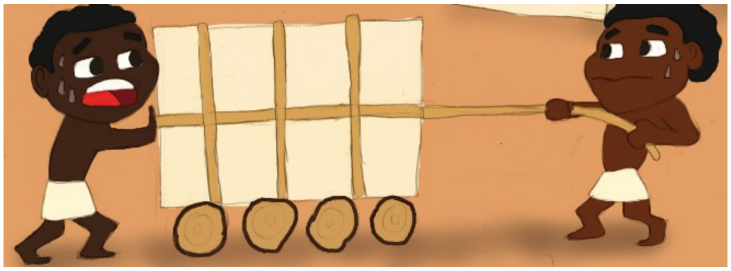


Figure 2: The round timbers used by Egyptians

Even though the round timbers helped in moving objects, the friction problem between the round timbers and the carried bodies remained as well as the friction between the trundles itself. The problem remained until Leonardo de Vinci realized that friction could be reduced if the rollers did not touch each other. He therefore designed separators allowing them to move freely and the bearing's ancestor was born but only on paper as shown in Figure 3**.**

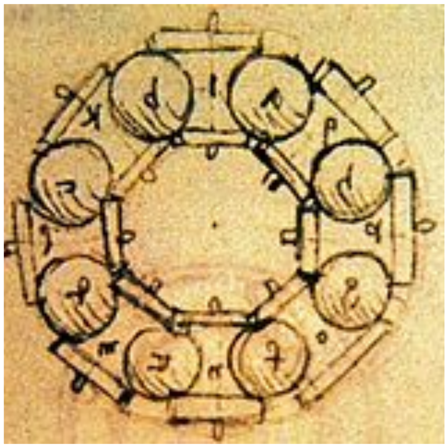


Figure 3: The drawings of Leonardo de Vinci of the first bearing [1].

Most ancient plain and rolling-element bearings were constructed from wood which was soon replaced by bronze. During their history over time, people would mold the bearings from different materials, ranging from ceramic and glass to the steel, bronze and other metals, all of which are being used in present times. Good rigidity can be provided even by very basic materials, for example, one can still find the wooden bearings today within old clock devices or t water mills, where the water itself acts as lubricant and cooler [2]. The modern bearings developed as the result of the significant progress in science, technology and manufacturing processes.

1.3 The Types and Uses of Bearings

There are about 50 types of rolling-element-bearings listed in most manufacturer catalogs. Samples of the most popular bearings are displayed in Figure 4. Each one has been designed for specific applications and has its unique characteristics.

Figure 4: Different types of rolling elements bearings [3]

Bearings are highly reliable components, and the vast majority of them will outlive the equipment on which they are installed. As displayed in Figure 5, bearings are generally classified according to:

- Type of load: radial, thrust, combination of both, steady or shock
- Magnitude of load
- Rotation speed
- Shaft misalignment
- Diameter of both shaft and housing
- Packaging constraints
- Desired life
- Maintenance requirements

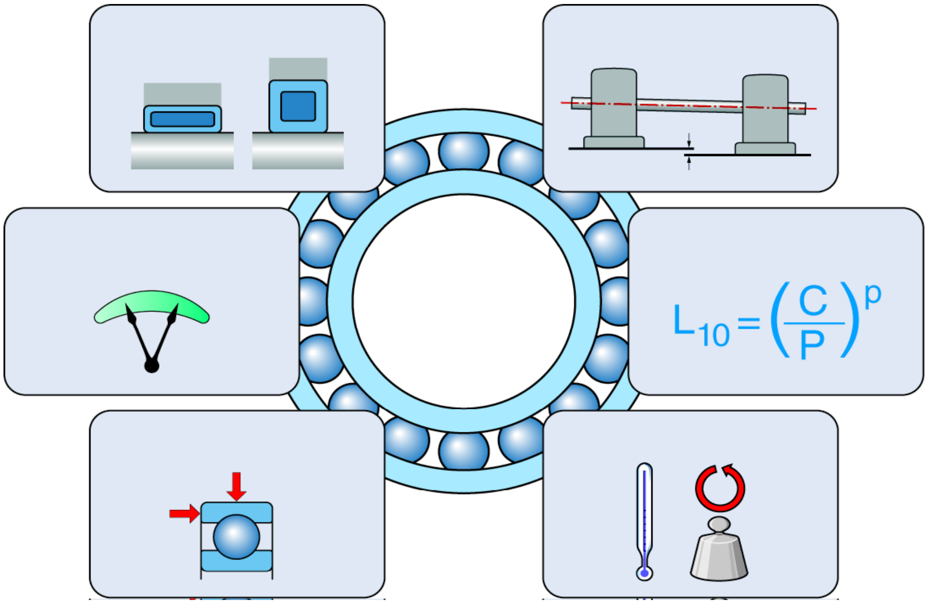


Figure 5: Selection criteria for bearings [4]

1.4 Type of Bearing Considered in this Investigation

Due to the simplicity in its geometrical details, the ease in its manufacturing process and the cheapness in its cost, with respect to the other types, the “deep groove” ball bearing is the most popular one on the market. For these reasons, the bearing to be considered in this investigation is a deep-groove ball bearing, type NSK-6208, with a bore diameter of 40 mm Figure 6. This bearing can withstand high radial loads and moderate axial loads, in both directions.

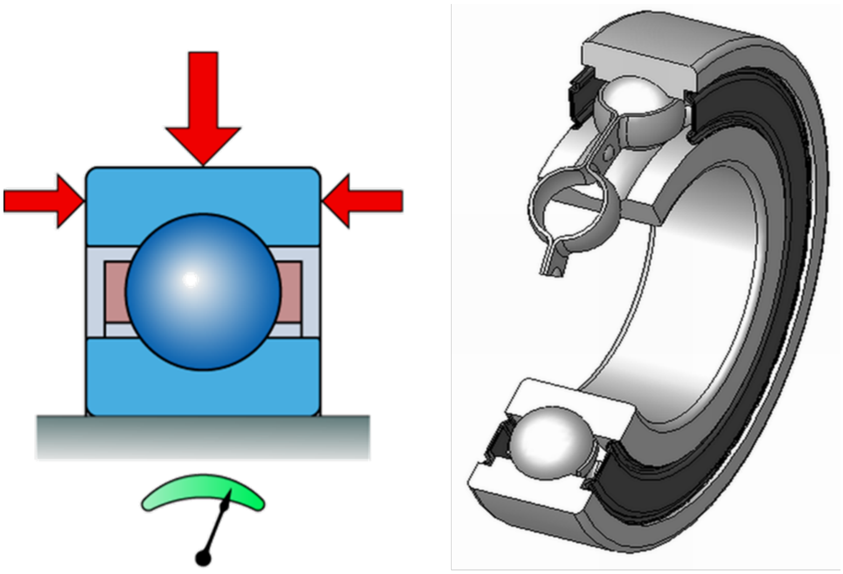


Figure 6: Test bearing of type NSK-6208, deep-groove ball bearing [5]

All specifications related to the NSK-6208 bearing shown in Figure 6 are summarized in Table 1.

Table 1: Test bearing (NSK-6208) specification

Parameters	**Values**	**Unit**
Inner Diameter (D_i)	40	mm
Outer Diameter (D_o)	80	mm
Pitch Diameter (P_d)	59.9948	mm
Ball Diameter (B_d)	11.8872	mm
Number of Balls (N_b)	9	balls
Width (B)	18	mm
Contact Angle	0	deg
Dynamic Load	29100	N
Static Load	17900	N
Limiting Speed oil	10000	rpm
Mass	0.366	kg

1.5 Importance of this Project to the Local Industry

Statistics provided by the International Trade Center [6] indicate that Qatar importation of bearings has significantly increased during the last ten years. Qatar's imports represent 0.03% of world imports for this product, and its ranking in world imports is 91. The total cost of the yearly imported during the period between 2001 and 2015 is displayed in Figure 7.

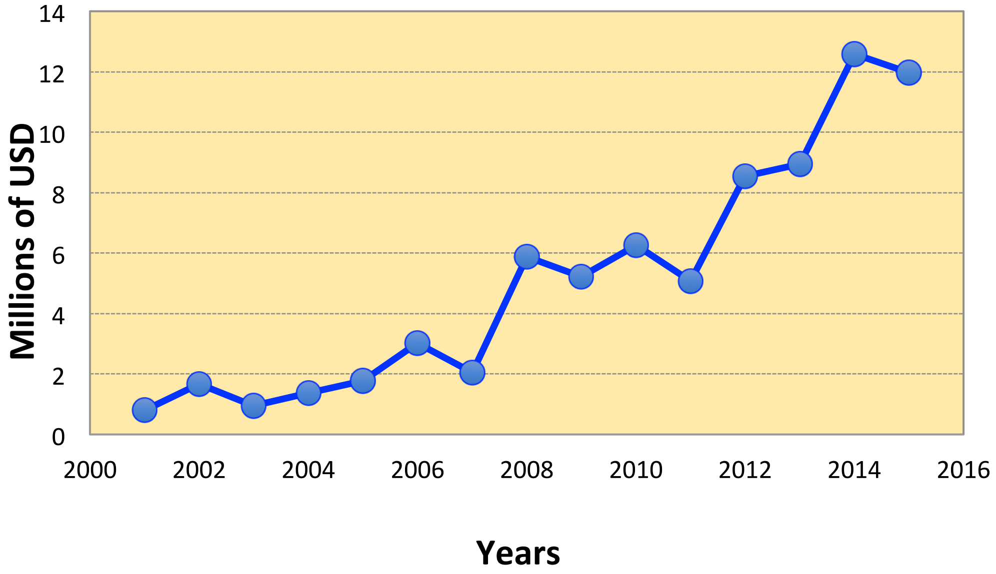


Figure 7: Qatar importation of bearings between 2001 and 2015, in US $ 1,000,000 [6]

According to the previous statistics, one can see that the bearings problem is very crucial for the local industry.

1.6 Aims and Objectives:

The principal objectives of this work are:

- To design and manufacture a test rig that could be used to experiment the condition monitoring of ball bearings,
- To find an appropriate way to seed defects inside bearings,
- To experiment the effect of localized surface defects on the vibration response of ball bearing.
- To carry out vibration measurements and provide all required means of signal processing to reduce the noise effects in the data.

- To compare the experimental results of damaged bearings with those obtained from healthy one, and draw all available conclusions.

The project will be conducted in three phases:

- Phase One: Designing, manufacturing and tuning of the test rig.
- Phase Two: Using the test rig and taking measurement.
- Phase Three: Analyzing the data and drawing conclusions.

CHAPTER 2 LITERATURE REVIEW

2.1 Plant Maintenance Practices

The conventionally known classic definition of maintenance states that it is “A combination of all technical administrative and managerial actions during the life cycle of an item intended to retain in it, or restore it to a state in which it can perform the required function” [7]. Plant Maintenance commonly involves the general maintenance practice, which is performed routinely in an industrial setting; it may include the specific periodic checkups of the equipment performance as well as the general cleanup of the premises. In its sense, the main point of the plant maintenance is to build and sustain the maximum productivity and safety of the working area. The management strategies, schemes, and methodologies of the maintenance depend on the machine type and are adjusted to the specific needs of the given enterprise.

In general, the most efficient maintenance strategy implicates that three main criteria for the equipment or the setting have to be ensured: the availability of specific functions in the best possible cost-effective way, the safety of the staff performing the maintenance tasks and the minimum adverse impact on the environment. To understand the abovementioned concepts of the maintenance, some terms must be described in more details:

Availability: It can be defined as a state in which the equipment can perform specific operations or functions to the measurable extent according to the needs called for. The ‘Federal Standard 1037C’ (USA) describes it as ‘mission capable rate’; [8]. Barlow et al. define the availability of repairable system as "the probability that the system is operating at a specified time"[9]. According to Blanchard [1998], availability is "a measure of the degree of a system which is in the operable and committable state at the start of a mission when the mission is called for at an unknown random point in time." [10].

Reliability: It can be defined as the probability for the function to be performed by a specific machine or its unit under given conditions in a definite period of time; by essence, it implies the resistance of system or equipment towards failure, or at least its ability to prevent catastrophic results in case of failure.

The reliability concept is best explained in the following Graph called ‘Bathtub’ curve, Figure 8 depicts the curve of failure rate over time. The first segment is conventionally known as ‘infant mortality’ and it accounts for the decreasing failure rates. The second segment under constant failure rates is popularly known as ‘random failures’. The third segment shows rising failure rates which are known as ‘wear-out failures’ [11].

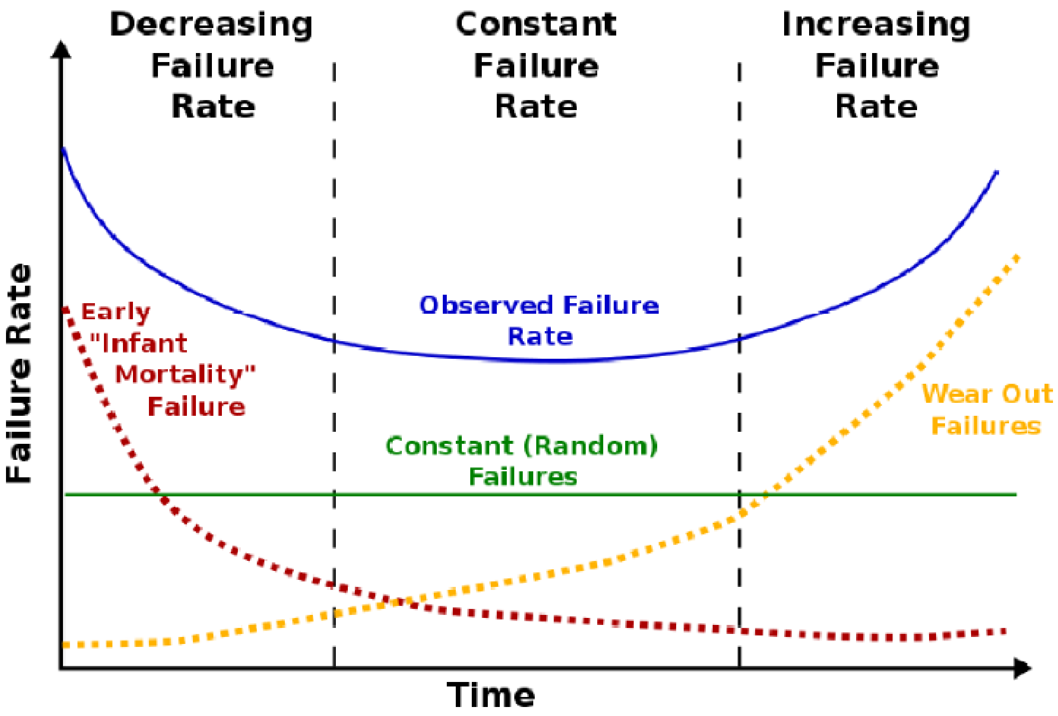


Figure 8: Bathtub Curve [11]

Maintainability: The definition of 'Maintainability' in plant maintenance engineering in complex emphasizes several points, including the feasibility of the system or equipment to be maintained in order to identify and isolate defects and their causes, correct the effects and their causes, perform new tasks as required, reduce the future need for frequent maintenance and adjust to possible alterations in the environment [12].

In some circumstances, maintainability may also be correlated with continuous improvement of the setting, implying by this the advancement of the system based on previous experiences with corrections of defects [8].

2.2 Importance and Need for Plant Maintenance in Industry

The maintenance management became a matter of concern together with rapid industrial development and modernization of machines after Second World War [13]. Increasing requirements for high efficiency and productivity raised the need for higher technology supplies. The frequent failures and decline in production would lead to big losses in financial terms for the industry. Thus the maintenance and its management became an essential part of the cost-effectiveness. According to Hansen I.H, the maintenance cost can account for the second largest part of whole enterprise budget, following only energy costs [14]. Obviously the reliability and productivity of the factory assets can be only achieved by respective maintenance tools adjustable to the setting, which will minimize the failure rates [15].

Mobley R Kieth underlines the significant deal of maintenance costs in total operational cost at the production setting, which can range from 15% up to 60% of the final product cost. Ineffective maintenance management causing the poor product quality and a decline in production time is estimated to account for more than 60 billion USD losses in industry setting of US [16].

2.3 Types of Maintenance

Di Leo et al provided the classification of maintenance methods, which divides them into three main classes:

1) Corrective maintenance – refers to repair of defected machines and components;
2) Preventive maintenance – the time-based maintenance with fixed schedules;
3) Predictive maintenance – implies the prediction of component condition to foresee the maintenance need [17].

2.3.1 Corrective Maintenance or Breakdown Maintenance

The abovementioned implicates that the maintenance is carried out only after identifying the fault and is directed towards restoring of the item back to proper working condition. So in general, it does not fix the item unless it’s broken. The industry set applying this kind of maintenance does not spend any costs until (or unless) the system fails. Due to the absence of preventive measure, it frequently leads to high maintenance costs, sudden unanticipated failures and secondary damages to the machinery. It even may lead to catastrophic consequences in some occasions, due to lack of control mechanisms. Its only advantage is that it does not include the unnecessary maintenance, which can be a part of other maintenance management methods.

2.3.2 Preventive / Scheduled / Planned Maintenance

This type of maintenance is carried out at specified regular intervals to reduce the chance of failure and downtime to a minimum. By consideration, the life period of a machine or system is not unlimited, and the failure probability will increase with age. Thus, the maintenance is performed in advance to prevent the failure and extend both lifespan and effectiveness of the system. Meanwhile, the precise estimation of the duration of the life cycle for the system of the machine is not an easy task to do.

Thus the methods of preventive maintenance are variable and depend on the specific type of the industry. Usually, new machines may have high chances of failure under improper installation, poor lubrication, poor alignment or balance and other circumstances impeding the system functioning. Also, in some cases, the parts could be replaced while it is in good condition and can perform the function probably.

The superiority of this type of maintenance lies in the convenience of planning in exact schedules of time and controllability of the technique, which gives a reduction in random failure rates, system downtime, decreased the chance of catastrophic failures and enables control over spare parts stock level.

2.3.3 Condition-Based Maintenance (CBM) or Predictive Maintenance (PDM)

By definition, this type of maintenance is the one carried out when the need arises [15]. It is achieved by continuous or periodical monitoring over the system or machine condition, accordingly with the need for the availability of the machine. This type of maintenance is initiated upon receiving the signal about faults from indicators in the incipient stages. The primary criterion, in this case, is to maintain the machine in the right condition at the right time. In practice, condition-based monitoring is performed by acquiring and analyzing the real-time data, in order to prioritize and optimize the maintenance activities and resources according to the demand.

Recently, more and more updated and interesting CBM methods are developed[18], though the challenge of detection and identification of faults at the ever-earlier stage is still remaining. In particular, the early detection of bearing defects is extremely important to allow maximum time for corrections to be carried out. This will also prevent the further damage of bearings, which can affect other components in the machine and extend its lifetime.

The rapid development of technology took launch together with the widespread use of Condition Monitoring since 1960's [19]. Under planned operation activity, all electrical and mechanical systems generate the characteristic signal, which is changing together with the changes in working mode of the system. Even the small differences from the normal signal can indicate an imminent fault development.

Condition Based Monitoring of the equipment implies the monitoring of a parameter of condition in this machine (this can be temperature or vibration behavior) so that a change in the latter would indicate a symptom of the developing defect. CBM allows the scheduling of maintenance or performance of corrective actions to avoid gross failures. However, for identification of obscure faults the deviation from normal value needs to occur. Industrial interest towards the need of condition monitoring has been increasing in both research and service provision fields recently [20-22].

One of the main challenges of CBM today is that changes in the system condition may be so tiny that they can be hidden by the noise in the system. Currently, engineers are focusing on combining modern transducers and signal processing techniques in order to differentiate between noise and significant trends indicative of failure. This can allow the detection of a fault at the earliest possible stage and even may predict the likely time for failure to occur [18]. In CBM system, the measured signal alterations follow the monitored parameter changes and in case of correct selection, will respectively measure the electrical and/or mechanical condition of the machine.

The signals used in CBM system can include vibration level, acoustic emission, and temperature variation. Other more traditional measurements, as lubricant condition, may enhance the quality of fault detection. All of the above supports to the planning of maintenance activities and their scheduling. The benefits of this type of maintenance are enormous, as it cuts down the maintenance costs, prolongs the system life and prevents catastrophic breakdown [23-26].

Condition Based Monitoring involves administrative and technical measures directed at maintaining or restoring the system or process to the condition that will allow performance of designed functions. The essence of this technique includes the detection of a fault, diagnosis of the cause of the fault, evaluation of its severity level and arranging modes for the fault correction. Under various advantages of CBM, the following can be emphasized specifically [27].

1. Through minimizing the frequency of system overhauls it significantly reduces maintenance costs, as it eliminates the number of unnecessary interventions;
2. The duration of intervention time is minimized because of the ability to provide advanced information about the fault severity.
3. Prevention and/or elimination of catastrophic failure.

Among the wide range of CMB techniques previously described, the vibration appears as the most powerful one. The vibration signature signal (vibration level or other) will most probably change over time together with the altered condition of all dynamic systems. The changed system signal gives the alert about the presence or onset of possible failure, which in previous times was usually masked by the background noise of the system. Signal processing techniques are applied more and more extensively in present time, as it enables separation of significant trends from random variations. This provides earlier diagnosis and longer time before failure onset that can be crucial for the due performance of the item responsible for production process or safety procedure. By this way, CBM provides a reliable technique, which can warn aboutany potential failure of critical items, in comfortable time ahead, and prevents the gross losses for production costs.

2.3.3.1 The Importance of Condition Maintenance and Fault Diagnosis in Industry

The ever-increasing competition on global market urges the industries to apply greater effort to the reduction of costs and increasing product quality permanently. At this point, one can consider that elimination of dramatic or fatal catastrophic failures indicates on successful performance of the company. However, small chronic failures, which are frequent, more prevalent and less visible, can apply even bigger defect and loss of productivity in sum, than the catastrophic failures would do [28]. Chronic failures result in frequent interruptions of the production process, the decline in product quality and increased production costs. It is estimated that total downtime caused by non-catastrophic failures is greater than due to catastrophic ones; this leads to outstandingly expensive losses, which greatly exceeds the maintenance costs [29].

A huge sum (billions of dollars) is spent on plant maintenance practices annually worldwide in industrial setting [30]. Maintenance costs are estimated to account for as much as one-third of productions costs in general [31]. The better availability and reliability of the system will obviously give substantial cost savings and improved profitability, which requires the implementation of effective CBM for the machinery [32].

The combination of CBM with regularly scheduled maintenance practice minimizes the downtime, increases productivity and thereby must support to increased cost-effectiveness. The machine availability can significantly be improved by the precise and prompt fault detection and diagnosis. This concept respectively led to the development of numerous CBM techniques, and particularly, vibration monitoring using time and frequency domains analysis, to improve the performance of the setting [24, 25, 33].

Earlier detection and diagnosis of potential failure enables the maintenance staff to initiate all necessary actions for correction, to reduce the production losses to a minimum[27]. In general, all industrial processes are based on the functioning of specific machines, whose reliability provides a smooth functioning of the system and the production line, while their malfunctioning can lead to high-cost failures.

Currently, research focuses on preventive maintenance which is vital for these machines [29, 34]. As reported by recent studies, the expensive downtime can be minimized and manufacturing efficiency, quality and safety be improved significantly by CBM technique applied with critical machines, alerting early about any potential failures [35]. CBM minimizes the rate of incidents related to secondary damage to nearby components when mechanical failure occurs in large scale. As mentioned above, traditional industrial plant maintenance implied that it was not attended until the machine was finally broken down. However, since 1990's, the development of inexpensive computerized devices and cost-effective sensor technology has allowed the industries to introduce preventive maintenance, which can identify the problems in the system and anticipate the maintenance needs long time in advance.

2.4 Bearing Failures

The definition of a bearing failure is an ambiguous issue as no author specifies what constitutes a failure or indicates the difference between damage and failure. According to the Macquarie dictionary, failure is the "non-performance of something due or required" [36]. According to Nowlan and Heap [37], failure could be defined as any identifiable deviation from original state, which is not satisfactory for particular function or user. This contemplation further extends to wider suggestions that borderline between "satisfactory" and "not satisfactory" does not only involve the function of the item but also may implicate the equipment nature upon its installation and operating mode as well.

Moreover, Nowlan and Heap give the difference between the concepts of Functional Failure and Potential Failure. Functional Failure stands for "the inability of an item to meet required performance standards" while Potential Failure is defined as "an identifiable physical indication that a Functional Failure is imminent".

Moubray provides the explanation of the P-F curve concept, which describes the changes of condition once the failure, has commenced Figure 9 [38].

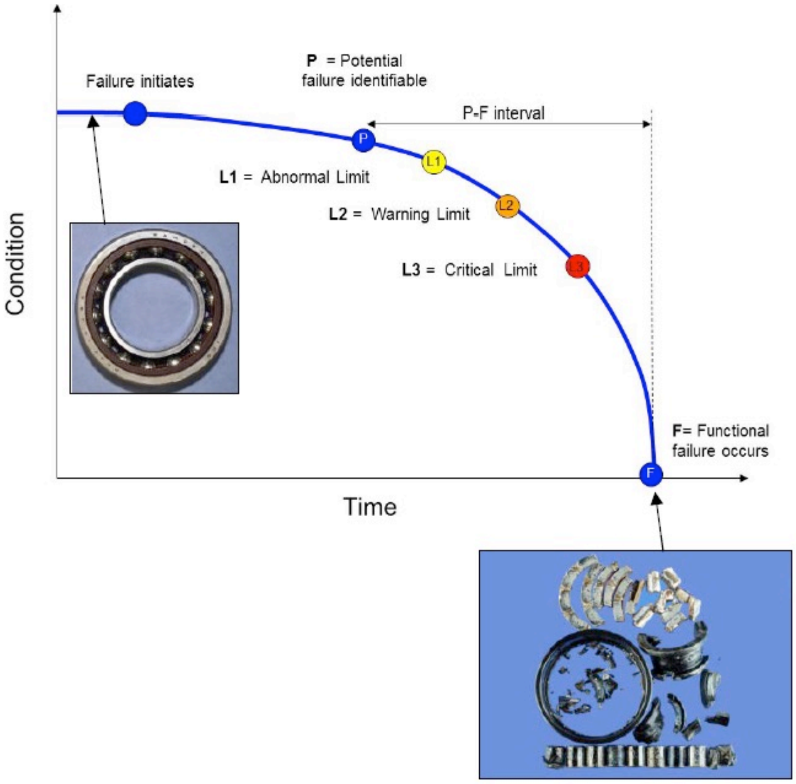


Figure 9: The concept of a P-F interval [38]

The point “P” on the curve corresponds to the potential failure; this is the point at which abnormal state can be actually identified. The point F corresponds to the time where a functional failure of the item or equipment has occurred. Respectively, one would raise a logical question: what is the optimal amount of notification signal for a functional failure? To say more simply, what length P-F interval should be. Although this cannot be always the case, traditionally it was believed that the earlier is the notification signal, the better is. For instance, very fine metal particles can be found in lubrication system during oil analysis. However, the items may have quite long residual life remaining. On the other hand, we can find out substantially less remaining life, if the amount of visible metal in the same system is measured by any of the specific methods (filter debris analysis, magnetic chip detectors, Hinductive wear debris sensor, etc.). A bearing can be run to functional failure under low failure consequences. However, a failed bearing becomes less evident and more important to define in cases where failure consequences are significant, or if complex and expensive machinery (e.g. aircraft system) is engaged.

According to Widner [39], the bearing can be considered as damaged if the contact surfaces have altered enough to apply adverse effect on their performance. Concerning the failure, he suggests that bearing is considered to have failed when the damage evolves to the point at which the bearing function is threatened.

According to ISO 15243 [40], bearing failure is defined as “damage that prevents the bearing meeting the intended design performance”. SKF [41] defines the life of a bearing as “the number of revolutions the bearing can perform before incipient flaking occurs”. By this definition, we can suggest that any detectable flaking on the bearing surface indicates a trivial sign of its failure. Although this may not always be the case, as the damaged bearings can also have residual life [42].

The definition of failure which relates to the prediction of bearing life is provided by ISO 281:2007 [43]. The latter states that the bearing life can be regarded as expired upon receiving of the first evidence of material fatigue on any of the bearing sub-components. This concept only fails to admit that the duration between identified fatigue spall and functional failure of the bearing can extend to a significantly long period of time and thus it's not practical to be detected in most of the systems.

Obviously, the acceptable degree of damage or spall should be dictated by operating context itself; however, sometimes-even aviation bearings still continue to perform their work even under the presence of fatigue spalling (carry load in a degraded state). Thus, as mentioned before, the acceptable degree of damage must be determined for a particular operating context in a particular case. Rolling-contact fatigue (RCF) is a very important terminology for tracking rolling element failure. RCF corresponds to the failure or removal of material caused by crack propagation, resulting from alternating stress field appearing close to and affecting the surface [44]. Choi and Liu [45] in their study defined two vibration limits from a laboratory test. The first limit was found to be at 0.2g RMS, and visual inspection demonstrated an initial spall with a diameter of approximately 600 microns. At RMS of 1.8g, the second limit was located, and that was confirmed by extensive raceway spalling. Based on their results, authors underlined that the conventional bearing RCF life is commonly defined as the number of loading cycles before the initiation of a spall.

This research [45] used the following definitions adhered to rolling element bearing condition, which actually depicts the journey of bearing lifetime from initiation of the defect to functional failure:

1. Benign wear: Non-RCF wear typically associated with progressing initial wear.
2. Damage: the first identifiable spall on any load-bearing surface. It does not exclude the bearing functioning.
3. Failure: where a spall is almost equal to the spacing between two rolling elements and the failure is the time when the machine should stop. A further operation may lead to significant secondary damage or functional failure.
4. Functional failure: at this point the bearing physically stops to carry load, stops to rotate or stops to function as intended.

2.5 Stages of Degradation

In general, there are four stages of degradation in bearing lifetime. The first stage is the defect initiation when the defect is just created and not disturbing the bearing function. In this stage, the remaining life is up to 10% of Lh_{10} (about months) and the temperature and noise are normal. No presence of bearing fault frequencies and Weak level of global vibration speed. Moving to the second stage where the defect starts to propagate, the residual life is about to 5% of Lh_{10} (about weeks). The housing temperature is normal, but there is a noticeable light noise and light increase of the global level of the acceleration vibratory. In addition, bearing frequencies can be detected on a logarithmic amplitude scale along with detectable resonance frequencies of the bearing that arise due to shocks (at high frequency). This stage is considered to be the pre alarm stage. For the third stage, the remaining life is less than 1% of Lh_{10} (about days). In this stage, there is a light increase of the temperature and audible noise level added to a strong increase of the global level of the vibration (in acceleration). The frequencies of bearing and harmonics are visible on a linear amplitude scale, which is a clear indication of the alarm state. Finally, at the fourth stage of degradation, it is necessary to replace the bearing immediately. In this stage the residual life of the bearing is less than 0.2% of the Lh_{10} (about few hours). Augmented noise and temperature levels appear to match with an increase of the global level of the vibration in displacement and speed. Reduction of the global level of acceleration can be noticed as well. Peaks at fundamental frequencies of the bearing are detected and related side bands too. Moreover, noise at high frequency (friction induced random vibration) is present [66]. It is essential to detect bearing defects in early stages to avoid catastrophic failures.

2.6 Fault Detection Techniques

2.6.1 Description of Techniques

Prevention of catastrophic failure and planning of effective maintenance hugely depends on early detection of mechanical faults in bearings. In present times condition monitoring commonly uses the techniques associated with human senses (vision, listening, touching), which employ the visual, aural or tactile inspection, smelling, and optical magnification [46]. The benefit of observations extends beyond to unmonitored equipment. The sensors are used to collect information about the condition of the system which makes them absolutely necessary for data acquisition and analysis. Therefore, both operation and maintenance staff must be trained observers capable of understanding the machine condition deeply based on this particular information.

Thermal analysis, oil debris analysis, and vibration analysis occupy the leading places among the number of approaches used to diagnose faults on the bearing system. In this chapter, those fault detection techniques will be discussed with special emphasis on the use of vibrations analysis method, as it represents the most widely and reliably used technique for condition-based maintenance in the industry today [16].

2.6.2 Thermal Analysis

In general, thermal analysis serves as a tool to give warning signals about overheating of the bearing system. Usually, it includes infrared thermography cameras or other devices of temperature monitoring. By this technique, we represent the change in a temperature gradient of the bearing component. Thermal analysis, however, cannot diagnose the type and size of the defect in the bearing system.

2.6.3 Oil Debris Analysis

The lubrication type for the bearing is usually selected accordingly with operating conditions and may be in liquid, grease or solid form. Debris analysis is mostly used with oil (liquid) lubricants, and its application is limited for grease or solid lubricants. In fact, bearing failure can result in the generation of significant debris in the oil systems of some machinery, such as aircraft turbine engines or helicopter transmissions.

Oil analysis program for bearing by default involves oils sampling, analytical tests, and interpretation of the data. The diagnostic tools for identification of bearing failure which pertain to oil debris analysis, include a number of techniques, such as elementary spectroscopy, wear particle analysis, fine particulates analysis, molecular analysis, and electrochemical chemistry. They give the information about the size, the form, and the quantity of debris in the system, by which the type of damage can be diagnosed actually. Akagaki et al. [47] demonstrated that the depth of rolling-contact fatigue wear couldbe diagnosed by a small amount of oil debris extracted from oil analysis. In the same study, the wear severity levels were better evaluated in the presence of large particles. The presence of wear particles served as a critical signal that bearing had to be replaced before the occurrence of the forced outage. Although due to material similarity, differentiation between damaged components of bearing could not be done by this type of analysis.

Combination of vibration analysis with oil debris analysis has shown to be more effective in terms of providing more detailed information about the fault location and severity as well as, it creates more reliable condition-based monitoring system in bearing compared with each individual system.

2.6.4 Vibrations Analysis Technique

Currently, around 80% of parameters measured by condition monitoring appear to be vibration-based [13] Vibration monitoring and analysis is the most widely applied method in CBM today. Vibrations can provide a lot of information about machine condition. Moreover, the fault condition in different types of systems can be explained by measurement and analysis of vibration response [48]. The fact that vibration spectrum can be collected for all systems consisting of rotating or moving elements makes the method of vibration-based analysis widely applicable for CBM practice. Together with other techniques, vibration analysis is commonly used in condition-based maintenance for monitoring and analyzing particular machines, equipment or systems on site. The main target of vibration analysis is to monitor the rotating device in order to identify progressing faults and eliminate the risk of catastrophic failure. This makes it the most conventionally applied maintenance practice throughout all strategic maintenance systems.

The widespread use of vibrations analysis technique made it synonymous with condition-based maintenance. From the very outset, this method relies on the instrumentation. About why is this method popular in CBM today, Mobley, R. K. in 2002 stated that “All mechanical equipment in motion generates a vibration profile, or signature, that reflects its operating condition. This is true regardless of speed or whether the mode of operation is rotation, reciprocation, or linear motion. Vibration analysis applies to all mechanical equipment, although a common—yet invalid—assumption is that it is limited to simple rotating machinery with running speeds above 600 revolutions per minute (rpm)” [16]. In addition to condition monitoring, vibration analysis method can be applied in diagnostic tools as well. Actually, for most systems which are used in manufacturing or assembly of the products, this method represents a primary diagnostic tool. Industries apply a wide range of non-destructive testing, which also employs vibration analysis techniqueto enhance performance and reliability of the plant.

Rotation of gears, shafts and bearings accounts for the specific vibration profile or signature in each particular rotating device. The great part of machine vibrations is contributed by rolling bearing elements, as they represent the essential part of rotating devices. This can be explained by the following mechanisms:

1. The structural element of bearing acting as spring and adding the weight to the system.

2. The bearing produces vibration in the system due to its time-varying forces which act as excitation forces. However, faults or defects in bearing components can significantly augment these forces.

In normal conditions, the natural symmetry in rolling bearing elements will most probably result in a healthy bearing to achieve a steady state dynamic equilibrium under constant load and speed. The vibration force will increase in case a surface defect develops on one of the bearing components. The presence of defect will cause the appearance of transient forces whenever defective surface comes in contact with another bearing component, ultimately leading to an acceleration of both components.

Nowadays vibration monitoring is the most popular technique for the diagnosis of rolling element-bearing faults. Since the early 80s, some researchers have published research and review papers on vibration signal analysis techniques and bearing defects diagnosis techniques. Kim and Lowe reviewed the importance of vibration and wear debris analysis techniques with regard to the railway freight car [49]. In their paper, McFadden and Smith [50] reviewed the use of High-Frequency Resonance Technique in vibration monitoring of rolling element bearing. In the early 90s, Tandon and Nakra [51] provided a comprehensive review of vibration and acoustic monitoring techniques for the detection of defects in rolling-element bearings. Their detailed work involved the vibration analysis in the timedomain and the frequency domain, acoustic emission techniques, sound measurement and shock pulse method. Another review by Tandon and Choudhury [52] referred to the use vibration and acoustic measurement methods for the detection of defects in rolling element bearings. In addition to multitude of techniques, this review particularly underlined the use of wavelet transform method and automated data processing techniques.

The main challenge in vibration diagnostics is to extract specific features from the signal and relate them to normal or faulty components of the bearing. In general, a raw signal is almost never used as it is, because of its high dimensional nature and the presence of noise. A feature extraction stage is usually applied to alleviate both of these problems related to raw vibration signal, in order to capture the most relevant information embedded in the latter.

As mentioned before, the bearing health can now be monitored through the number of widely available condition monitoring techniques, such as temperature, vibration monitoring, wear debris analysis, motor currentanalysis, etc. and preferences depend on the system itself for getting the most valuable information. However, vibration monitoring appears to be the most convenient and useful technique due to its reliability and high sensitivity in diagnosing of the fault severity, which makes it most widely used method too in systems involving bearings [50, 53]. Nevertheless, other measures can also improve the performance, although they require more expensive equipment and are therefore less cost-effective [54].

2.6.4.1 Bearing Prognostics Using Vibration Signatures

Prediction of the remaining life for a bearing is one of the significant areas of interest in the research concerning the condition monitoring. A lot of bearing manufacturers consider this issue while using the trends extracted from vibration signal. Although, regardless of the importance of this issue, research papers on bearing prognosis are scant. The reasons involve insufficiency of available vibration data and complicated assessment of the remaining life of bearing, even with accurate vibration history [55].

Statistical estimation of bearing life, applying data from laboratory experiments is the main target of study in this field. The bearing fatigue life is currently calculated by the Standard Life rating formula provided by ANSI/AFBMA, which carries the fatigue life theory in its core concept [55]:

$$L_n = a_1 a_2 a_3 \left(\frac{C}{P}\right)^k \qquad \textbf{Equation 1}$$

Where:

- $\mathbf{L_n}$ is the rolling contact fatigue life in revolutions × 10^6,
- $\mathbf{a_1}$ is a reliability factor,
- $\mathbf{a_2}$ is a material factor,
- $\mathbf{a_3}$ is a lubrication factor,
- **C** is the basic load rating of the bearing,
- **P** is the equivalent load applied to the bearing,
- and **k** is a coefficient equal to 3 for ball bearings and 10/3 for roller bearings.

The above calculation should assumingly give a precise estimation of bearing life. However, real-life conditions quite frequently are significantly different from those given in the equation above. Therefore, evaluation of remaining life based on vibration measurement still remains a considerable challenge.

2.7 Analysis Tools

The precise diagnosis of the defect largely relies on the application of appropriate signal analysis technique. In a real situation, vibration analysis is a consecutive process which interprets a compilation of various data collected from particular devices or systems. In such cases, the machine or system will yield a quite complicated vibration spectrum due to the presence of various vibration sources. Thus, the vibration signal obtained from transducer appears to be rather complex (as a result of summation from different sources). Also, this signal is very likely to be non-stationary (due to progressing fault) and contaminated with artifacts from background noise. Several sources in the system produce specific responses for each, which are integrated into one complex signal. So obviously, some unnecessary information must be filtered out to obtain more clear data Figure 10 shows how all the machine components can contribute to the overall vibration.

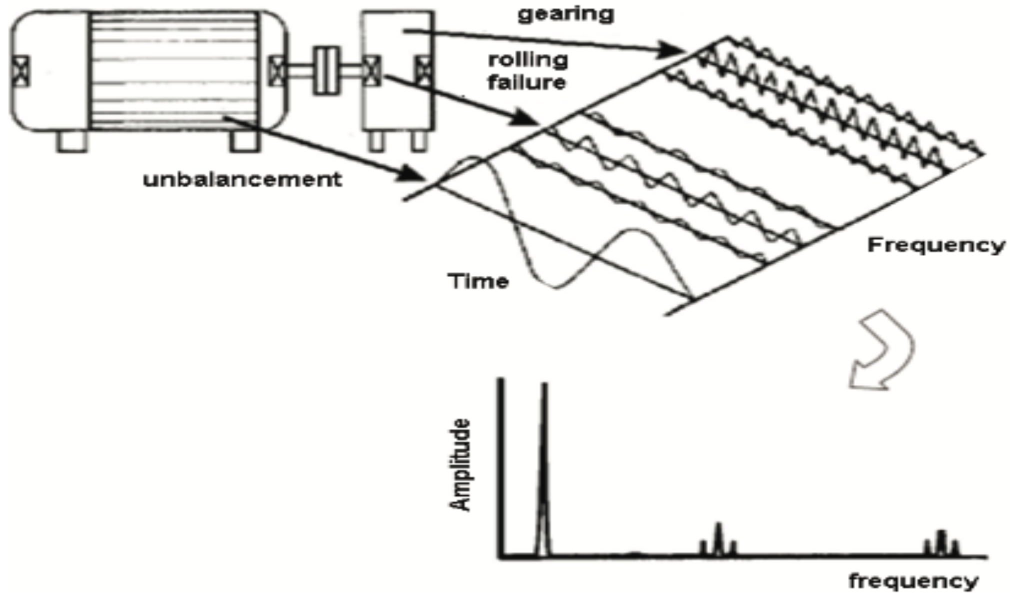


Figure 10: Contribution of machine components to overall vibration [56]

Signal processing serves for extraction of useful information related to any faults in the bearing. Among numerous signal-processing techniques, three of them need to be mentioned: time-domain analysis, frequency domain analysis and time-frequency domain analysis [57, 58]. They are briefly reviewed below.

2.7.1 Time Domain

The time domain format plots the vibration data as amplitude versus time. It is referred to as most convenient and simple technique for analyzing the vibration signal waveform. Defect condition is diagnosed and assessed by using statistical parameters of vibration signal in time domain. However, any detection based on time-domain parameters requires that the defect should be advanced enough to be recognized through background noise.

Variable indicators that are related to the shape of the time signal can be observed and determined while experimenting. In general, an indicator's value does not have fundamental significance. However, its evolution over time is usually indicative of the occurrence or propagation of a defect. Based on time-domain data, the statistical scalar parameters commonly used for diagnosing bearing faults are peak, root mean square (RMS), crest factor (CF), kurtosis (KU), impulse factor (IF) and shape factor (SF)[59].

Table 2: The definition of time domain parameters as in Matlab library

Indicator	**Equation**
Peak	$\mathbf{a_{peak} = sup_{1 \le k \le N} \lvert a_k \rvert}$
Average	$\mathbf{\bar{a} = \frac{1}{N} \sum_{k=1}^{N} a_k}$
Root Mean Square	$\mathbf{a_{RMS} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} a_k^2}}$
Crest Factor	$\mathbf{CF = \frac{a_{peak}}{a_{RMS}}}$
Kurtosis	$\mathbf{KU = \frac{\frac{1}{N} \sum_{K=1}^{N} (a_k - \bar{a})^4}{\left(\frac{1}{N} \sum_{K=1}^{N} (a_k - \bar{a})^2\right)^2}}$
Shape Factor	$\mathbf{SF = \frac{a_{RMS}}{\frac{1}{N} \sum_{K=1}^{N} \lvert a_k \rvert}}$
Impulse Factor	$\mathbf{IF = \frac{a_{peak}}{\frac{1}{N} \sum_{k=1}^{N} \lvert a_k \rvert}}$

Kurtosis value, Crest factor, Impulse factor and Clearance factor all represent non-dimensional statistical parameters. Theoretical kurtosis of bearing with good surface finish is 3; the kurtosis value will increase along with deterioration of surface finish, however, kurtosis is not sensitive towards changes in loads and speeds [60]. In work published by Li and Pickering [61] it was demonstrated that all of the above parameters (Crest factor, Kurtosis value, Impulse and Clearance factors) are sensitive to early-stage fatigue spalling. According to the studies by Karacay and Akturk [62], although the above-mentioned time domain parameters demonstrate the damage at ball bearing, they still cannot provide the information about precise defect location (inner/outer race, cage or roller).

Time domain formats are commonly applied to reciprocating and linear movement devices. These formats are handy for general evaluation of the system to detect and analyze minor changes in operations. However, the efficient interpretation of data from time domain can be very challenging. The vibration data in time domain format involves an integrated spectrum of all system sources at the particular time, making it difficult to identify the specific spectrum of the definite source in this case.

As a conclusion, we can explain the essence of time domain as to obtain data regularly throughout the entire lifecycle of the machine or system and consistently compare it with historical data gathered at same fundamental frequencies. The downside here includes significant variations in practical plant operations which may fluctuate over time. In addition, time domain analysis cannot indicate the location of bearing failure component.

2.7.2 Frequency Domain

The most popular approach for bearing fault diagnosis nowadays is the spectral analysis referred to as frequency domain. Frequency domain analysis performs converting of measured time domain signal into an equivalent frequency domain signal (F = 1/T), which is followed by analysis of signal component frequencies. Jean Baptiste Fourier was the first one formulating the mathematical equations to visualize the frequency spectrum of the time-based signal [63]. Figure 11 depicts the sample of time-frequency transformation:

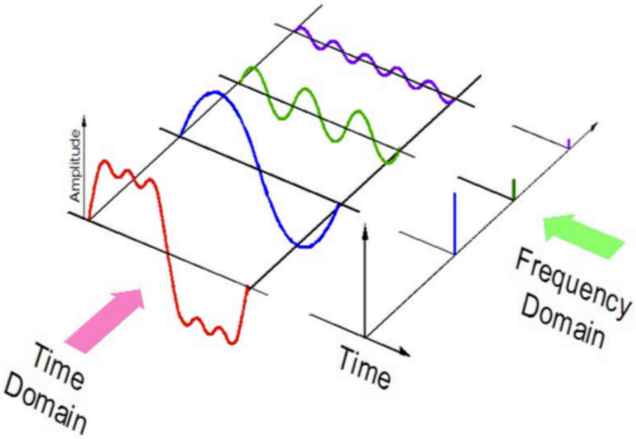


Figure 11: Signal view in time and frequency domain [63]

Transformation of the acquired signal into frequency domain results in the distribution of energy from generated pulse signal over a range of frequencies. By this approach, we can obtain individual frequency components with respective amplitudes.

The results of transformation should be acquired rapidly in real-time analysis. The efficiency of discrete Fourier transformation is provided by the applicability of FFT algorithm to the calculation of spectrum composed of the data blocks, which can be performed in real time analysis in fast mode [64].

As described above, the frequency domain techniques use a Fast Fourier transform (FFT) which mathematically converts time-domain vibration signals trace into the series of discrete frequency components. The Fast Fourier Transform (FFT) represents an algorithm which is used to calculate the Discrete Fourier Transform. The frequency domain plot measures of the frequency (X-axis) versus amplitude of displacement, velocity or acceleration (Y-axis). The ability and convenience of easy detection of certain frequency components under concern are the main superiorities of the frequency domain format over time domain analysis. The fluctuating sequence of arising and diminishing peaks in the spectrum was explained in detail by James Taylor [65].

Another popular technique applied for the detection of imminent failure of rolling element bearing is the envelope analysis [48, 50, 57]. This powerful technique is the most commonly used method by present time [69]. Many names are usedwith reference to the same method, including high-frequency resonance technique [50], amplitude demodulation [70], demodulated resonance analysis and narrow-band envelope analysis [71, 72]. The deteriorating rolling element bearing produces modulated random noise, and the envelope analysis is the technique able to extract the periodic impacts from this background noise. This process is highly effective as it can be performed even under low energy signal generation, while it’s hidden deep to other vibration profiles produced by rolling element bearing.

The rolling element or other surface in bearing passing over the presumable defect on any part of the affected rolling element will produce an impulse or impact of very short duration. As the energy of this impact distributes at low level over a wide spectrum of frequencies, the bearing defect is difficult to be identified by normal spectrum, considering the additional vibration from other machine elements. The natural frequency of bearing element is triggered by the impact mentioned above, increasing the vibration energy to significantly higher frequency compared with the vibrations produced by other elements in the system. Each bearing element has a characteristic defect frequency which can be theoretically calculated (this will be expressed in more details in the following part). Periodic impacts are revealed as a peak with some harmonics in envelope spectrum at characteristic defect frequency, which corresponds to the faulty element in bearing. Thus the envelope analysis represents a precise technique for the detection of bearing defects. Its efficacy has well been demonstrated by number of researchers [50, 70-73]. The important tool in envelope analysis is Hilbert transform, which was reportedly used for detection and diagnosis of system faults [74, 75]. As explained by Spyridon and Ioannis [76], FFT can easily identify the bearing fault, while envelope analysis serves more as a tool for bearing failure detection.

The extensive review of the literature shows that time domain techniques can only detect the presence of faults in bearing but fail to identify their location, whereas frequency domain techniques can identify the location of the fault(s) as well.

2.7.3 Time-Frequency Analysis

Traditional Fourier Transform is not the suitable for detection of signals with time-varying frequency content because the time signal is averaged by this method and non-stationary characteristics could be lost. To keep the time-frequency picture of a signal, it's recommended to use methods to show how the frequency content of the signal changes with time. Time-frequency techniques represent the one-dimensional signal to two-dimensional function of time and frequency which make it an effective tool to analyze a non-stationary signal instead of using the direct Fourier transform [57]. There are different methods that use time-frequency concept such as, Short Time Frequency Transform (STFT), wigner-ville, wavelet transform, continuous wavelet transform and envelope Spectra of wavelet transform. In this research the focus will be more in time domain and frequency domain analysis rather than time-frequency analysis because the defects were used in this study were single localized defects under steady speed and the time-frequency techniques are most common in analysis of multiple defects or Time-Varying Speed Conditions [68].

2.8 Bearing Faults Frequencies (BPFO, BPFI, Cage and Ball Spin Frequency)

The vibration analysis of bearings has nowadays become an intensive realm of research. As referred to this topic, researchers tend to classify the bearing defects according to their coverage range – point (localized) defects and generalized defects [77]. The local defects (mostly scratches) appearing on bearings include spalls, pits or localized damage showing up on raceways and rolling elements. The presence of local or single-point defects in this case facilitates the bearing failure diagnosis, as they generate the characteristic frequency, which can be calculated by kinematic considerations, meaning the bearing geometry and rotation speed [51].

Generalized defects, on the other hand, involve deformations arising at the time of manufacturing, incorrect setup or wear damage. Usually, such defects produce broadband vibrations, thus requiring more detailed methods for the detection. As mentioned above, the precise localization of point defect (e.g., determining the location of fault whether it is on the roller, inner or outer race) cannot be done by application of crude time-domain parameters only.

Exactly like a fingerprint, any bearing infected with a surface defect generates a set of unique frequencies, which values are related to the geometry of the bearing and the running speed of the shaft:

- BPFO is the Ball Pass Frequency on Outer race, or simply the characteristic frequency of the outer ring.
- BPFI is the Ball Pass Frequency on Inner race, or simply the characteristic frequency of the inner ring.
- FTF is the Fundamental Train Frequency or simply the cage characteristic frequency.
- BSF is the Ball Spin Frequency, or simply the ball characteristic frequency.

Logically, the calculation of essential point defect frequencies in rolling element bearing can lead to the identification of the exact failure location in the bearing. Assuming a configuration where the outer ring is fixed and the inner ring, attached the shaft, is rotating at a constant speed S, the bearing characteristic frequencies are detailed in the following equations:

$$\mathbf{BPFI} = \mathbf{S}\frac{\mathbf{N_b}}{\mathbf{2}}\left(\mathbf{1} + \frac{\mathbf{B_d}\cos\boldsymbol{\alpha}}{\mathbf{P_d}}\right) \qquad \textbf{(Equation 2)}$$

$$\mathbf{BPFO} = \mathbf{S}\frac{\mathbf{N_b}}{\mathbf{2}}\left(\mathbf{1} - \frac{\mathbf{B_d}\cos\boldsymbol{\alpha}}{\mathbf{P_d}}\right) \qquad \textbf{(Equation 3)}$$

$$\mathbf{FTF} = \mathbf{S}\frac{\mathbf{1}}{\mathbf{2}}\left(\mathbf{1} - \frac{\mathbf{B_d}\cos\boldsymbol{\alpha}}{\mathbf{P_d}}\right) \qquad \textbf{(Equation 4)}$$

$$\mathbf{BSF} = \mathbf{S}\frac{\mathbf{P_d}}{\mathbf{2\,B_d}}\left(\mathbf{1} - \frac{\mathbf{B_d^2}\cos^2\boldsymbol{\alpha}}{\mathbf{P_d^2}}\right) \qquad \textbf{(Equation 5)}$$

Where :

- $\mathbf{N_b}$ is the number of rolling elements,
- $\mathbf{B_d}$ is the ball diameter,
- $\mathbf{P_d}$ is the average (pitch) diameter,
- $\boldsymbol{\alpha}$ is the contact angle.
- $\mathbf{S}$ is the rotation speed of the shaft (supposed to be the same as the inner ring)

The defect frequencies explained above usually do not go beyond the low-frequency range for normal speeds, accounting for less than 500 Hz in general. However, the practice shows that the slipping or skidding in rolling element bearing can result in the slight difference of these frequencies from the calculated values [78]. Some studies have indicated that finding a significant peak at these defect frequencies within the direct vibration spectrums obtained from defective bearing is related to significant defects [79]. The latter is explained by masking of vibration signal from bearing by noise or vibration derived from other sources, which happens almost in every case unless the defect is large enough to produce a stronger signal [69, 79]. Tandon and Nakra [80] have also demonstrated that direct spectral analysis is able to identify the large-sized defects only.

Ray highlighted the condition under which diagnosing of bearing defect becomes complicated [81].

In general, studies have reported that identification of these rotational frequencies results in a successful diagnosis of the bearing defect [80] Moreover, the presence of a defect on moving element (e.g., inner race or rolling element) was observed to give the spectrum with sidebands which are about the components at characteristic defect frequencies [80] The expressions for frequencies and relative amplitudes of different spectral lines have been provided by Tandon and Choudhury [52], based on the flexural vibration of races occurring as a result of a localized defect on one of the bearing elements.

CHAPTER 3 EXPERIMENTAL SETUP AND INSTRUMENTATION

3.1 Test Rig Selection and Design

3.1.1 System Design

A test rig is required in this project to measure the vibration generated by a damaged bearing under specific load and rotational speed. This test rig will be used to support/mount the bearing, rotate the bearing at a required speed and apply load on the bearing. The test rig system is designed to take into consideration the ease of replacing the bearing for each test run. The system is selected and designed carefully to offer the following features that allow for testing of bearing condition. These functions are expressed in Table 3, and the details for each of them is mentioned in the following sections.

Table 3: Bearing test rig features.

	Features	Requirements
1	Support for the shaft	To support the rotating shaft and the testing bearing as well as, provide static and dynamic stabilities.
2	Source of rotation	An electric motor (AC or DC) that generates the rotating motion of the bearing and the shaft on which is installed.
3	Load on the bearing	A loading device that applies load on bearing to assure for detection of faults in the rolling elements.

Some extra details shall be investigated carefully, such as:

- Type and Size of the test bearing.
- The connection between the motor and the shaft.
- Shaft and bearing arrangement.

3.1.1.1 Rotation Source

As the project started initially without a particular allocated budget, our strategy was simply to use the lathe machine as a supporting device. The lathe-machine shown in Figure 12 has exactly the physical characteristics needed for this project:

- A mechanical frame that could support/hold the system.
- An electric motor, with controlled speed that could drive the shaft in a rotational motion.

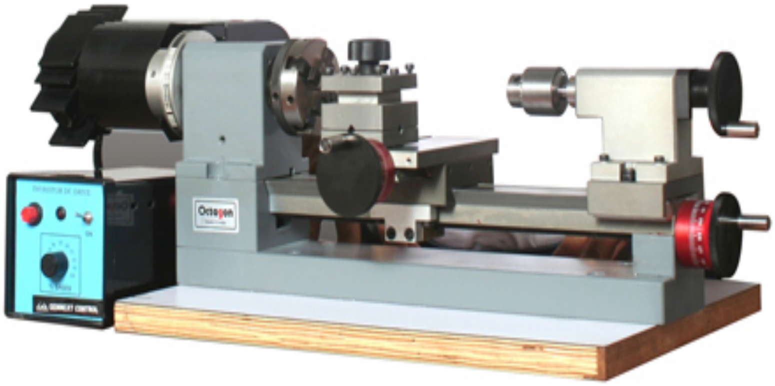


Figure 12: Lathe machine as supporting device

However, this option has been ignored and dropped because of its structure complication, with many mechanical components that may affect the overall vibration response later.

By dropping this solution, it was necessary to build a new test rig machine to conduct the experiments.

3.1.1.2 Design of the Motor-Shaft Connection

As displayed in Figure 13, there are three possible ways to transmit the rotational motion from the driving motor to the shaft.

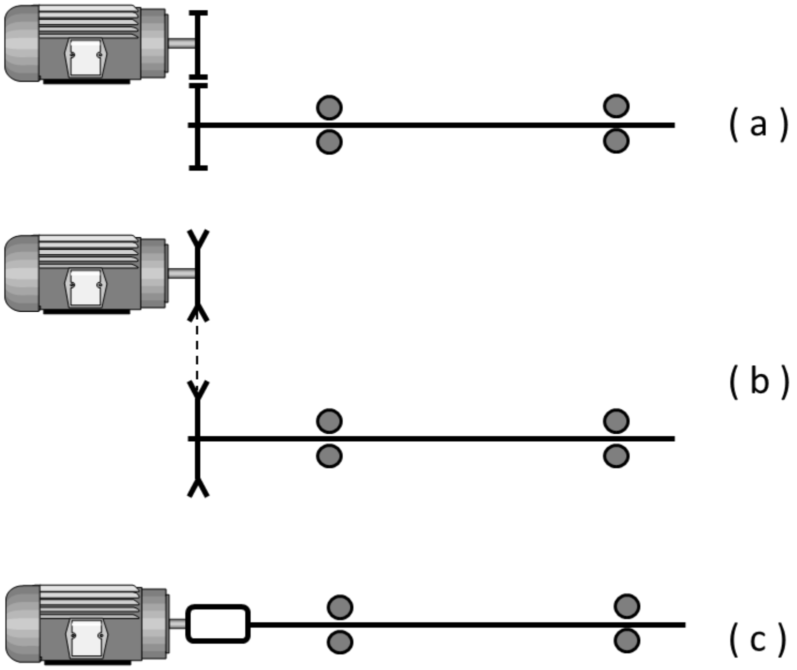


Figure 13: Power transmission options; (a) Transmission with gears; (b) Transmission with belt and pulleys; (c) Transmission by direct coupling

All three solutions are technically possible to use. However other criteria such as manufacturing, cost, and efficiency made the coupling appear as the most appropriate solution for transmitting the rotational motion from the driving motor to the shaft. Many couplings, with different shapes and different sizes, are available. However, the best couplings for this design are the flexible ones. When the coupling is flexible Figure 14, it could accommodate any residual misalignments and prevents vibrations to be transmitted between the motor and the rest of the system.

Figure 14: Flexible coupling

3.1.1.3 Design of the Test-Bearing location

As shown in Figure 15, there are three ways to locate the test bearing on the supporting shaft:

- The test bearing can be simply one of the supporting bearings.
- The test bearing is an additional bearing mounted out of the supporting principal bearings, at the extremity of the shaft.

- The test bearing is an additional bearing mounted between the two supporting principal bearings.

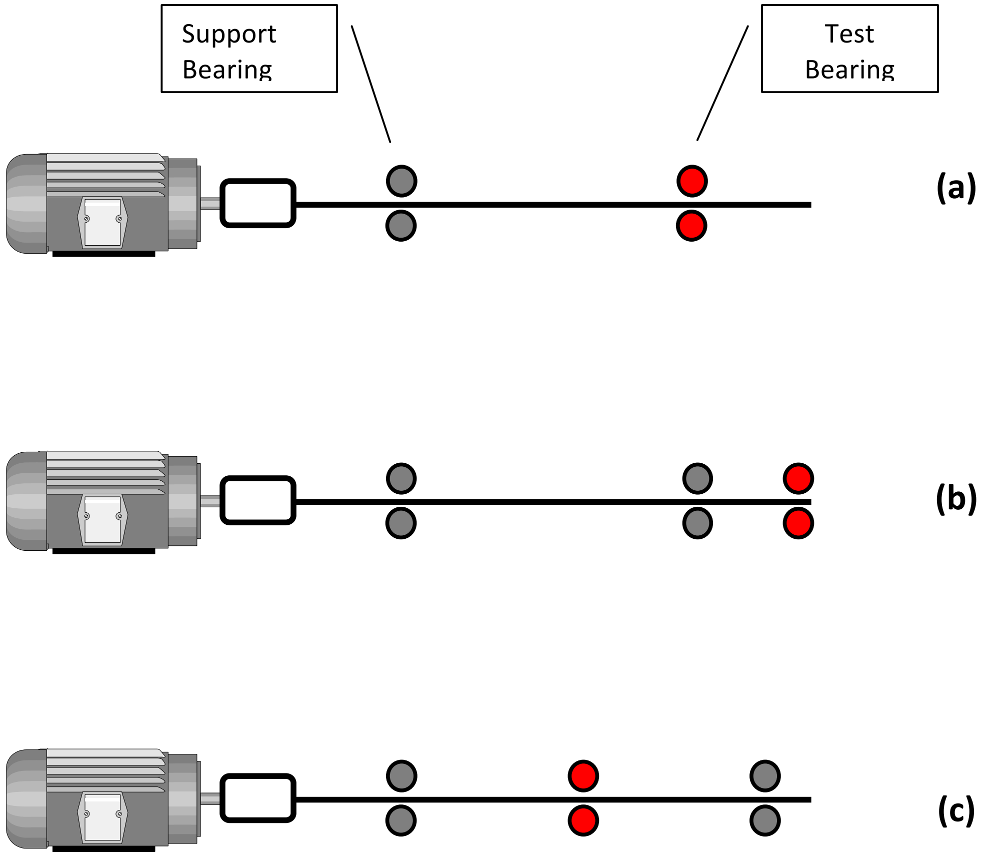


Figure 15: Test-Bearing Mounting; (a) Test Bearing is one of the supports; (b) Test Bearings is at the extremity of the shaft; (c) Test Bearing is between the two supports

Theoretically, the three solutions could be used. However, several criteria should be considered and examined to decide which design is the best one. In particular, the testing bearing is to be mounted and dismounted frequently. Therefore, case (b), where the tested bearing is placed at the extremity of the shaft seems to be the most appropriate design even it will not allow for applying high force on the defected bearing.

3.1.1.4 Design of the Loading System

Figure 16 illustrates three different possibilities of loading systems:

- A hydraulic loading device
- A thread loading device (screw + nut)
- A dead weight device

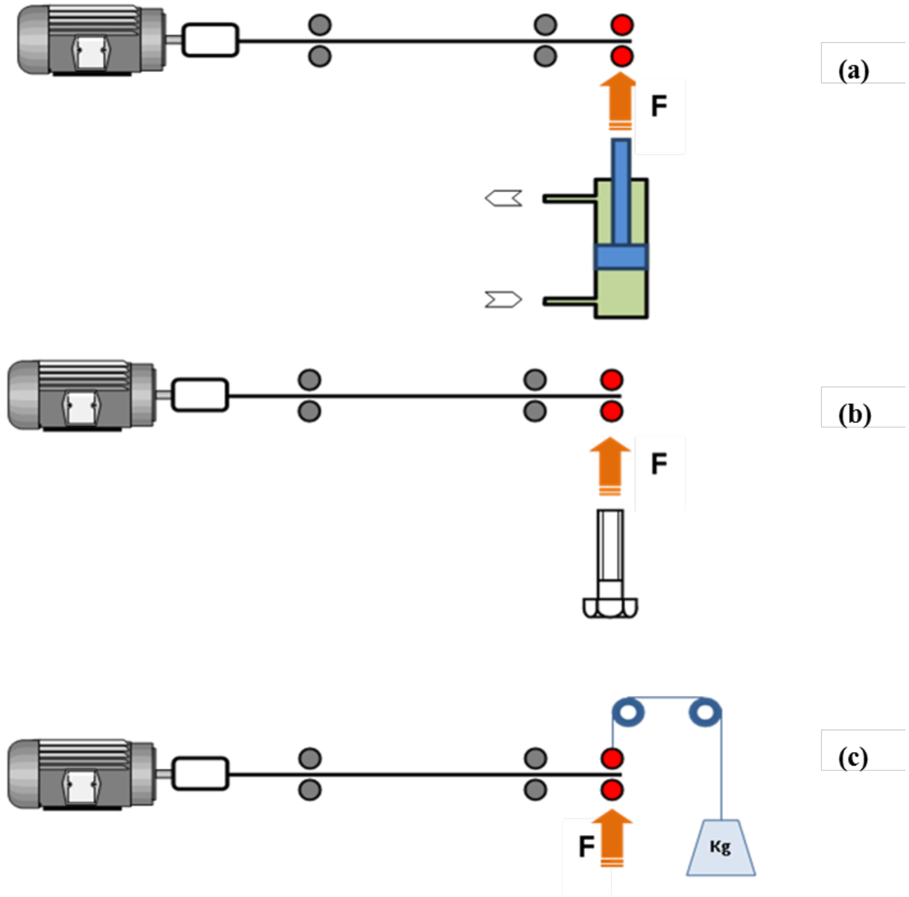


Figure 16: Loading System; (a) Hydraulic Solution; (b) Screw Solution; (c) Dead Weight Solution

The selection of the best solution is based on several crucial facts:

- The experiments to be conducted on this test rig may last for long time periods therefore, the applied forces should remain steady and stable as much as possible.
- The applied load should be enough to make the effect of defects clear as it is in the actual operating conditions and in the same time not very high to damage the system.

The most suitable solution (that offers a steady state loading, not very expensive and requires the minimum of space) is the solution based on thread loading device.

3.1.2 Design Summary

After all components of the system have been identified and selected, the design of the whole system started, including the motor, the connection between the shaft and the motor, the main structure arrangement of the bearings with the shaft and the loading device. However, because of budget limitation and a shortage of time, we decided to look for existing equipment in the labs, with all needed requirements and specifications instead of manufacturing the whole system entirely. Among the available devices, the system which looks the most appropriate and requires the minimum of modifications and maximum of convenience is represented in Figure 17.

This device is a “Machinery Fault Simulator”, built by “SpectraQuestInc” and designed to study the signature of common machinery faults, such as unbalance,

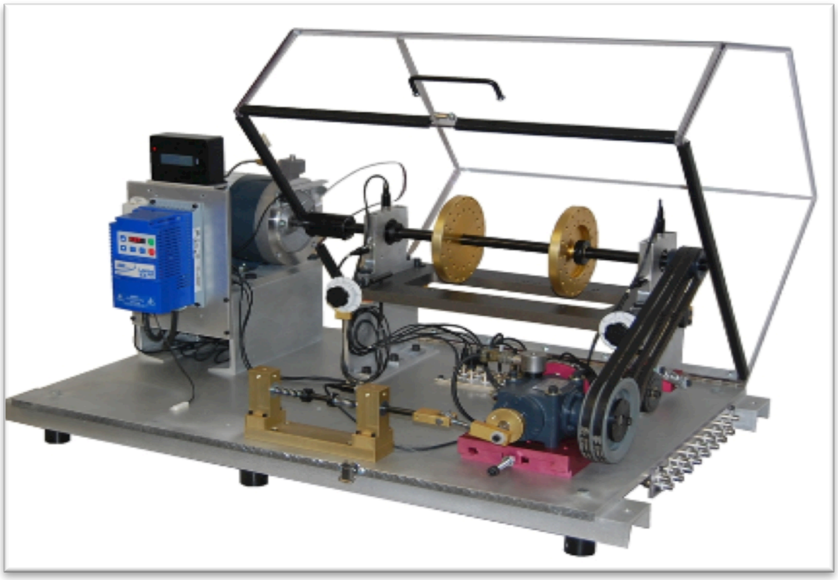


Figure 17: Machinery Fault Simulator (MFS) from SpectraQuest, Inc.

alignment, resonance, bearing, belt faults, etc.

This machine was purchased for more than ten years ago and never been used during the past period. To make it fit for our research need, the machine will require some essential modifications.

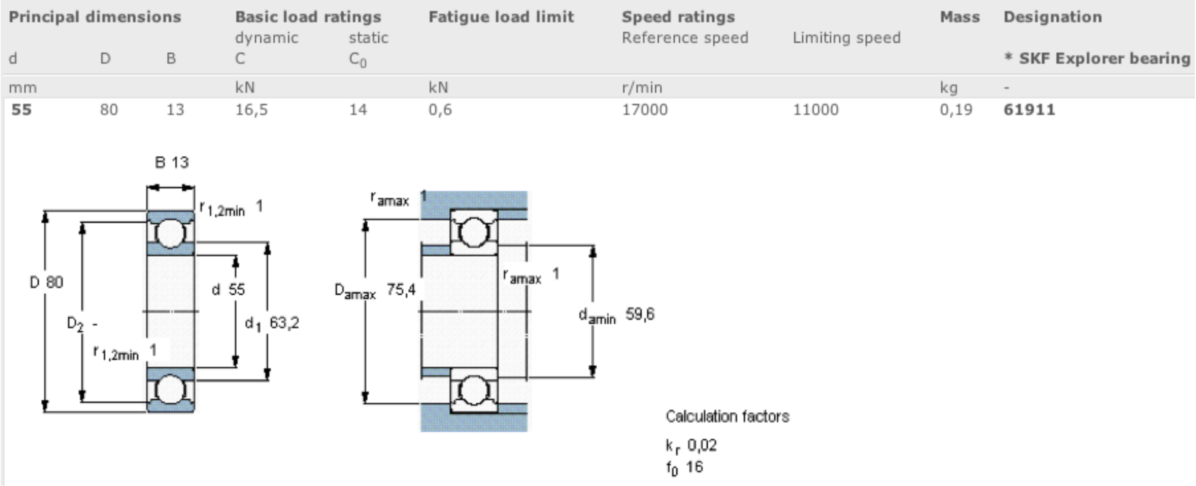
3.1.3 Modification for the Machinery Fault Simulator (MFS)

Several parts of the original machine had to be removed and replaced with new ones. These parts are:

1) Rotating Shaft.
2) Bearings housing.
3) Loading system.

3.1.3.1 Bearings Selection

All the bearings should be selected carefully before designing and manufacturing the shaft and the housings. The design of these components depends on both the bearings dimensions and types. In this machine, there are two types of bearings to be used. One is for supporting the shaft, and the other is for the testing purpose. The tested bearing should be big enough to make the defects seeding process on the raceways simple and easy. Therefore, a bore diameter of 40 mm was chosen (bearing type NSK-6208). According to the previous choice, we designed the shaft and selected its supporting bearings. A bore diameter of 55 mm was found to be adequate for this case (SKF-61911). Figure 18 below, shows the supporting bearings details.



Principal dimensions			Basic load ratings		Fatigue load limit	Speed ratings		Mass	Designation
			dynamic	static		Reference speed	Limiting speed		
d	D	B	C	C_0					* **SKF Explorer bearing**
mm			kN		kN	r/min		kg	-
55	80	13	16,5	14	0,6	17000	11000	0,19	**61911**

Calculation factors

k_r 0,02

f_0 16

Figure 18: SKF-61911 bearing physical and running specifications

3.1.3.2 Shaft Design

There are different constraints to be taken into consideration when designing the shaft. These constrains are:

- The total length of the machine plate,
- The supported and tested bearing dimensions,
- The alignments of the machine's shaft with the motor shaft
- The shaft weight.

By taking these restrictions into consideration, a whole mechanism was designed. Moreover, because the mounting and dismounting of the bearing is a difficult operation, time-consuming and may permanently damage the bearing or the shaft, an innovative solution based on elastic expandable geometry was adopted at the right end of the shaft.

The final design of the shaft is represented in Figure 19.

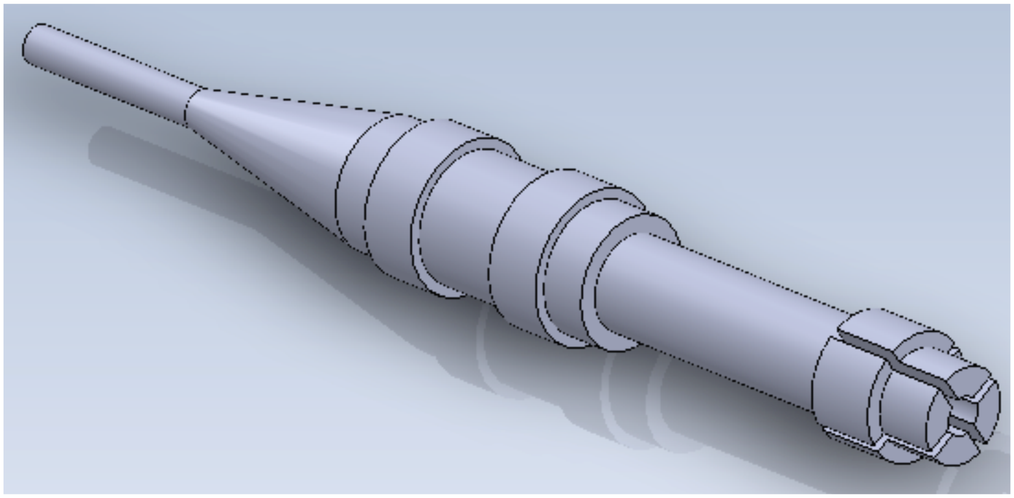


Figure 19: CAD drawing for the final design of the shaft.

3.1.3.3 Bearings Housing Design

There are two different types of housing to be designed:

- The first housing is for supporting the 55 mm bearing.
- The second housing is for supporting the 40 mm bearing.

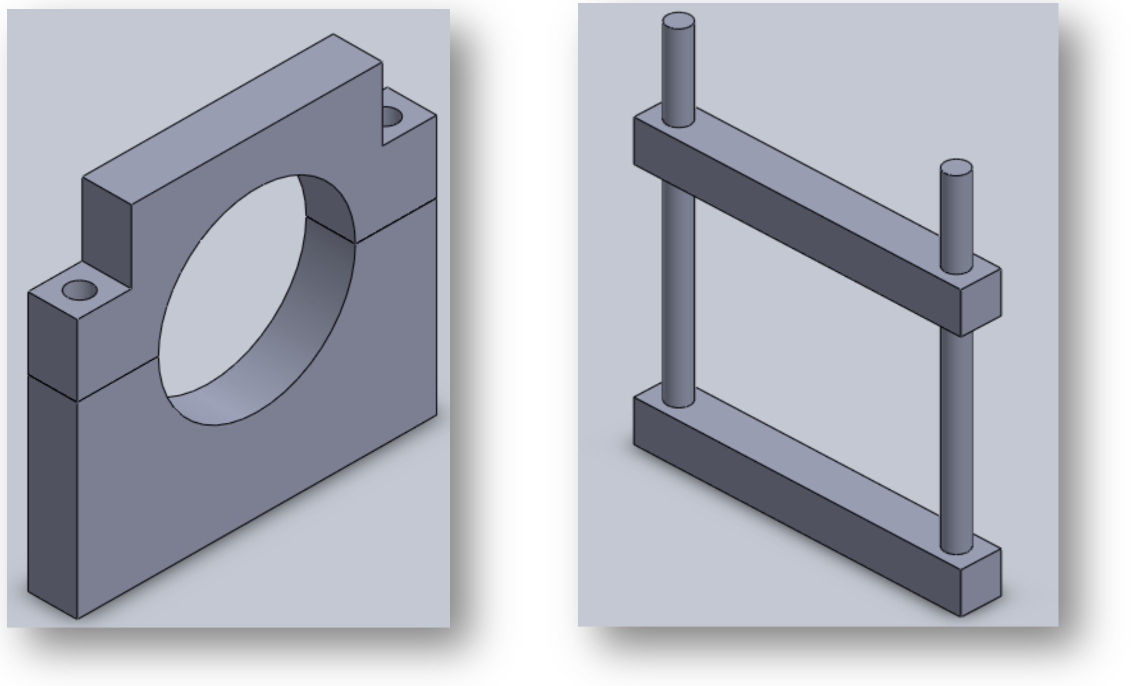
Each one of the two housings selected for the retaining of the support bearing SKF-61911is designed in two parts. The lower part will be fixed to the base-plate and should contain two threaded holes that fit exactly with the dimensions of the original housings. On top of it, the upper part will be fastened to secure a good positioning of the bearing.

The second housing assigned for the tested bearing is designed to ensure the following tasks:

- Transmit a radial load to the bearing,

- Allow a simple and quick mounting and dismounting of the tested bearing without affecting the alignment of the shaft,
- Hold permanently (by a stud) the vibration sensor.

Both designs of housings are displayed in Figure 20.



(a) **(b)**

Figure 20: CAD drawing for housing: (a) Housing for supporting bearings, (b) Housing for tested bearing.

3.1.3 System Assembly

During the assembly of new components, several minor problems were encountered and solved. Although the flexible coupling was mounted, the misalignment between the motor shaft and the designed shaft was found to generate a high level of unacceptable vibration, as the machine was initially un-tuned. Several attempts were made to correct this problem by adjusting the base plate with the rest of the machine Figure 21.

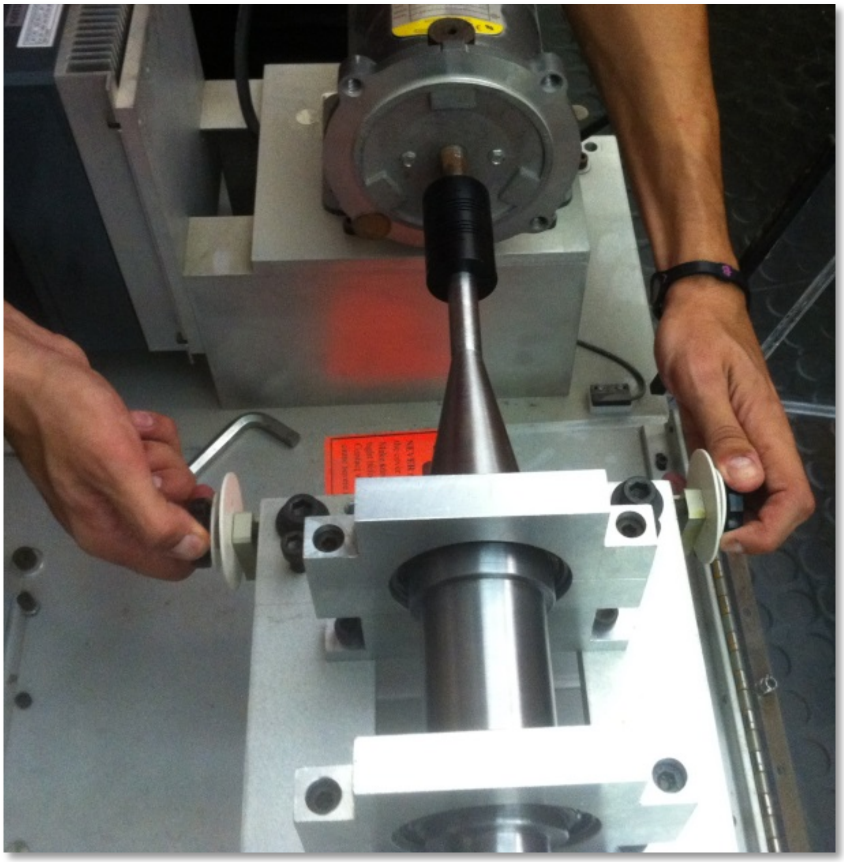


Figure 21: Adjusting the plate to reduce the misalignment problem

By solving the misalignment problem, the machine was tuned and finally ready to be used Figure 22.

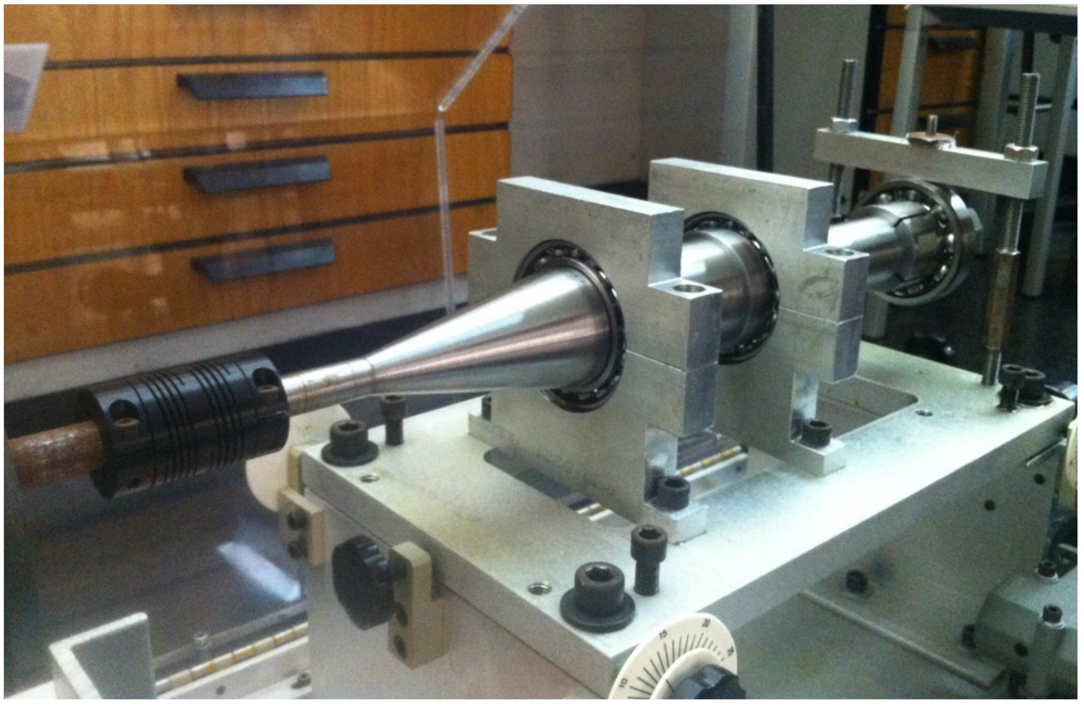


Figure 22: Final assembly of the system

3.2 Seeding of Localized Defect

The different possibilities for defect insertion are discussed in this chapter, and the final choice is explained.

3.2.1 Defect Characteristics

In general, the bearing can contain both localized and/or distributed defects accounting for the damage. Localized defects commonly develop due to fatigue and include the cracks, spalls or pits. On the contrary, distributed defects often result from manufacturing flaws, such as rough and wavy surfaces, misalignment of races or off-size rolling elements [77].

Condition monitoring and system maintenance basically rely on the vibration signals caused by localized defects, while the signals resulted from distributed defects are used in quality assurance monitoring. This study focuses on localized defects only. These defects may cause the damage to both outer and inner races, as well as for cage or the rolling elements Figure 23.

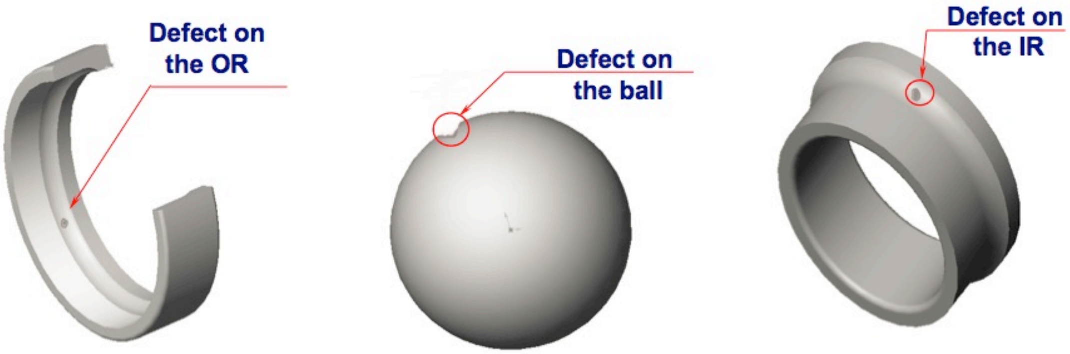


Figure 23: Different locations of localized defects causing injury to a ball bearing

3.2.2 Methods of Seeding a Localized Defect

To seed localized surface defects inside the bearings, four different methods were initially considered:

- Apply very strong acid solution to erode the selected part of the material (Acid Attack)
- Impact the surface by a sharp falling object. A special device is needed to achieve such idea.
- Drill with a very hard tool (diamond or tungsten-carbide) to make an indentation on bearing surface.
- Use Electric Discharge Machining (which was not available at the beginning of the project).

The acid attack consists in dropping small amounts of a very corrosive acid on the bearing to create defects. Two principal reasons made this choice not appropriate for our case:

- This method is not safe for the user
- It would be almost impossible to accurately control the size of the defects created on the bearing.

The idea of impact method is to use the potential energy of a falling mass to seed the defects in the required location. The energy of a falling mass is transmitted to a sharp tool (indenter) that makes a defect in the bearing. To let the impacting system work correctly, it is necessary to use an indenter with a material that is just as hard or harder than the bearing material. In this technique, varying the mass, falling height and the indenter size, can change the size of the defect.

Using a hard tool to drill in a bearing surface is another technique that could be used to produce a faulty bearing. In this method, a drill bit with a very hard material,i.e. diamond or tungsten carbide is used to make a scratch or indentation in the bearing material. In this method, the tool diameter and the applied pressure control the required defect size.

In the EDM an electrode is used to produce an electrical spark on a piece of work. The spark itself represents a visually detectable evidence of electric current. The electric spark mentioned above generates a huge amount of heat with temperature reaching from 8000^0C up to 12000^0C, which can melt down almost any material. This spark is localized and targeted very precisely, thus it only causes the damage to the surface of the material.

This process is one of the most accurate manufacturing processes in use today and would, therefore, have allowed for easy control of the size and location of defects being seeded inside the bearing. Unfortunately, the EDM machine was available only one year before the completion of the project.

3.2.3 Seeding Defect Using Impact Tool

3.2.3.1 Dismounting the Bearings

NSK 6208 deep groove ball bearings were used in this experiment. To dismount the different parts of the bearing, the heads of the rivet were simply removed by drilling through each one of them Figure 24-a. To avoid deformation of the cage during the drilling process, a special mold was prepared from epoxy clay (made by combining resin and hardener) to support the bearing correctly Figure 24-b.

Figure 24: Dismounting the bearing: (a) Rivet head removal, (b) Epoxy clay mold to hold bearing cage, (c) Fully dismounted bearings

3.2.3.2 Controlled Defect Insertion - Impacting System

The defects that occur in bearings in real life are usually on both the outer and the inner races (rings) of a bearing. Therefore, an impacting system was designed and manufactured in Qatar University to seed defects in these locations [82]. The designed system used the potential energy of a falling mass to seed the defects Figure 25. The kinetic energy of the mass was transmitted to a sharp tool that made a defect in the bearing. The sharp tool used for this purpose was a tungsten carbide-tipped dead center that is used in lathe machines.

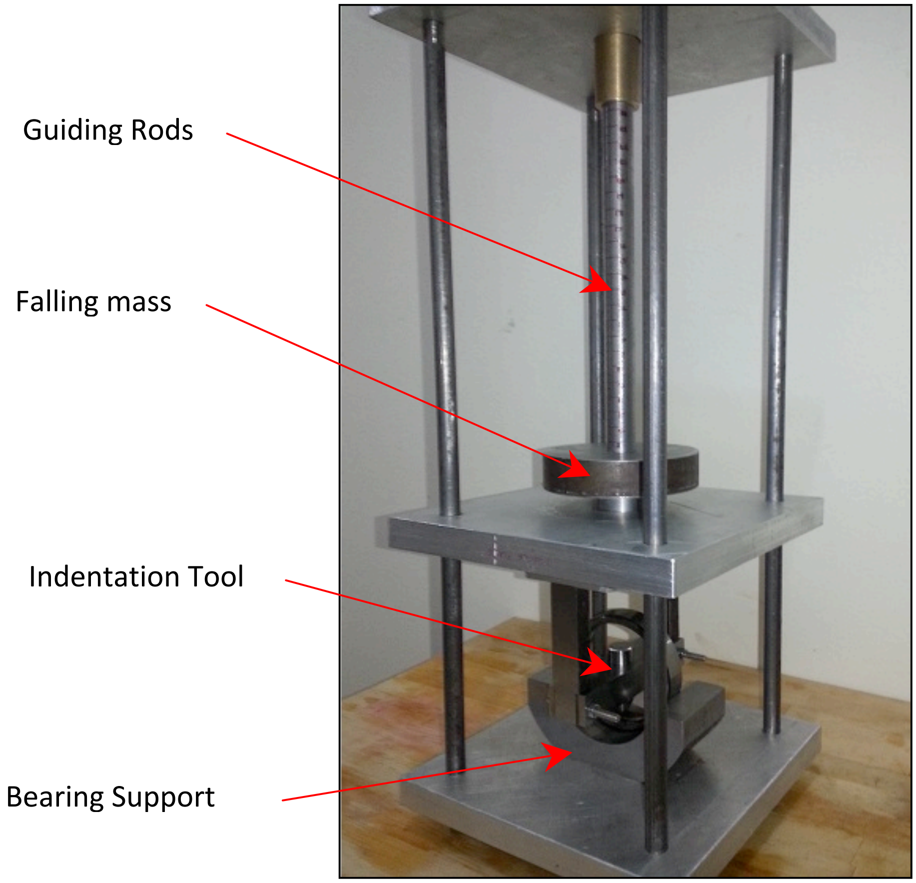


Figure 25: The impacting system [82]

To control the size of the seeded defect, the relationship between the mass’s drop height and the defect size should be understood beforehand. Initially, three different masses were manufactured (0.666 kg, 1.408 kg and 2.843 kg) and each mass was dropped from different heights. Using these different defects, a calibration curve was generated Figure 26.

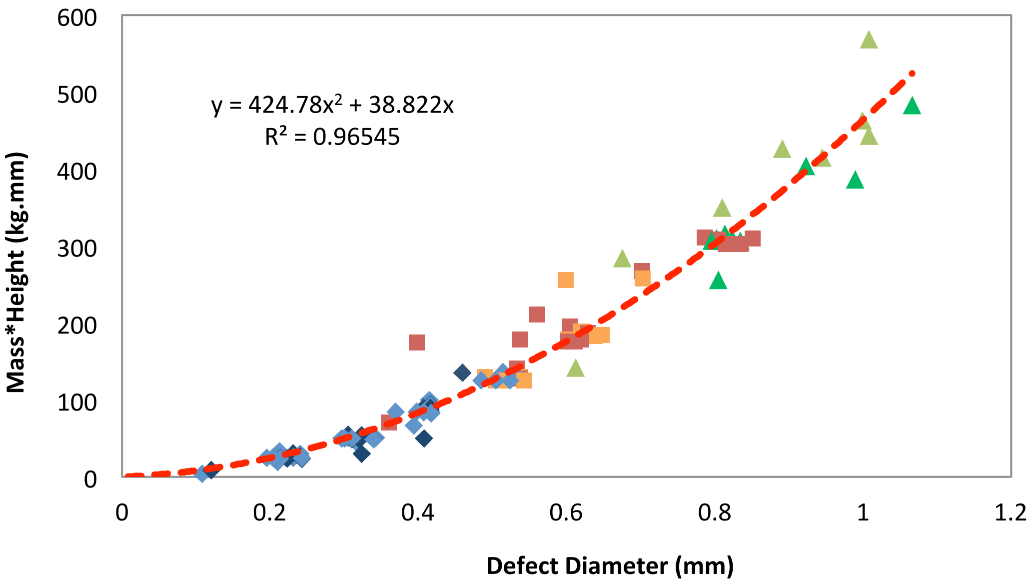


Figure 26: Variation of defect diameters with respect to the product of the mass and the height of the dropped weigh

After seeding the defects, a USB digital microscope was used to measure the size of each defect Figure 27. The defect sizes were measured in the rolling direction of the balls. The microscope was calibrated before each use to ensure the reading accuracy. The system was found to seed very tiny defects on the raceway of rings (around 0.1 mm) with a good accuracy.

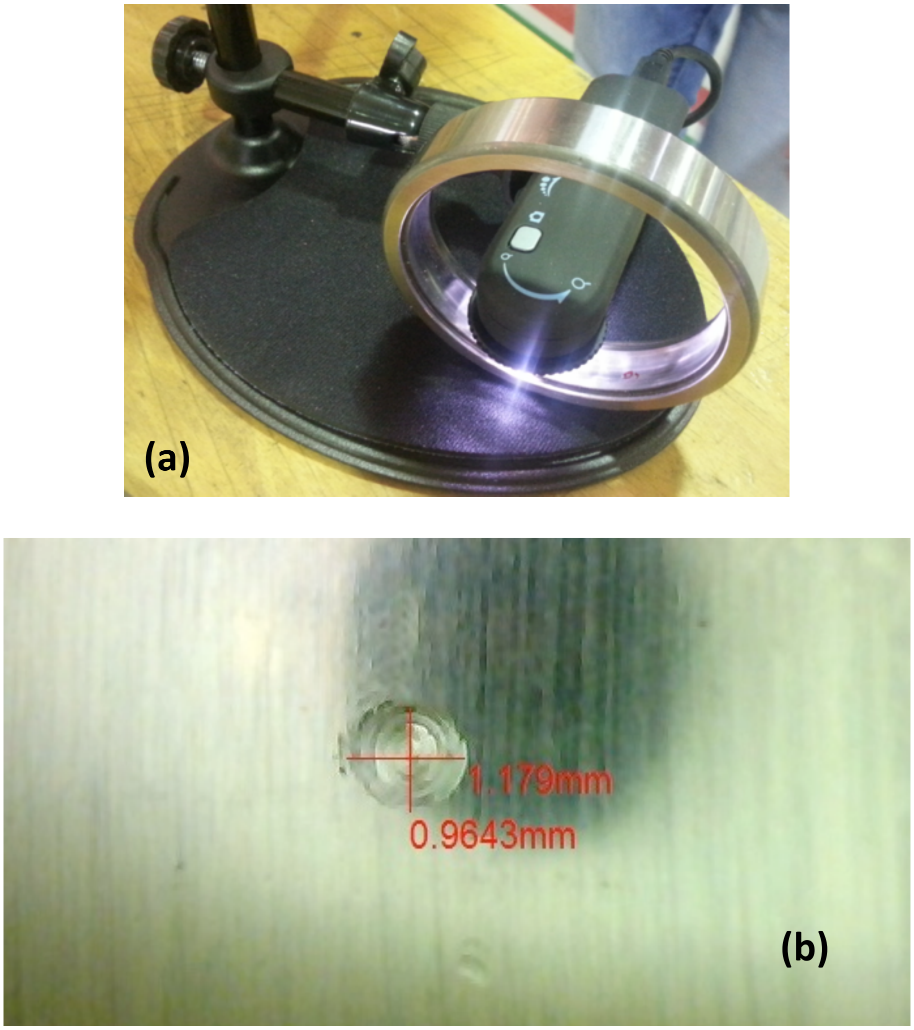


Figure 27: Microscopic observation of defects: (a) Observation of outer ring defect,
(b) Shape of inner ring defect under microscope

3.2.3.3 Remounting the Bearings

Once the defects were correctly seeded into their appropriate locations, the bearings were then reassembled back into their original configurations. To avoid any possibility of openings, a set of 3.2-mm rivets was used to close the bearing cages Figure

28-b. Finally, the mounted bearings were lubricated and tagged Figure 28-c. During all the previous steps, particular effort was made to keep the balls safe and clean to avoid any damage or scratching that may affect the overall vibration response of the bearing when remounted.

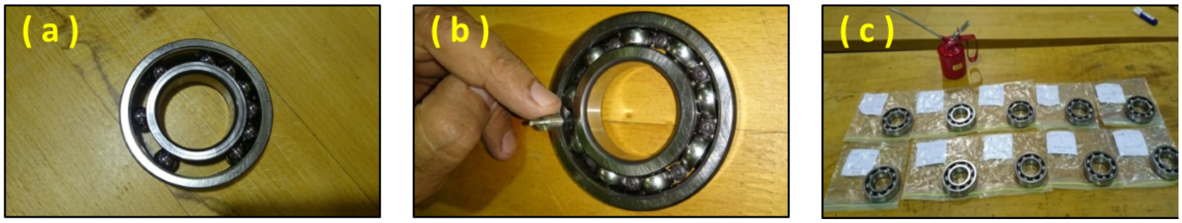


Figure 28: Remounting the bearings: (a) Replacing the balls inside the inner and outer rings, (b) Closing the bearing with rivets, (c) Lubricating the defective bearings

3.2.4 Seeding Defects using Electric Discharge Machining

Several months after the starting of the experimental work, the department of mechanical engineering at Qatar University finally got an EDM, model ET 400 CNC, displayed hereafter in Figure 29.

Figure 29: Electric Discharge Machine, type: ET 400 CNC

The previous technique of seeding defects was found to be very risky and harmful for the bearings (requires the dismounting of the bearing before making the defect and remounting it again). Moreover, the totality of damaged bearings obtained by that method was found to produce a high level of noise in their vibration signals.

Because the EDM technique is a very accurate manufacturing method, and able to seed defects on outer or inner races without opening the bearing, it was concluded that using an Electric Discharge Machine would have been the ideal solution for seeding defects in this research. Immediately after the new machine was installed (December 2016), all the experiments were repeated based on this new method.

The first step in the EDM process was to design and prepare the electrode. The electrode material could be one of two: Graphite or Copper. Both of them were tried. Because of its brittle behavior, the graphite electrode tended to fracture easily in case of any small vibration. Therefore, a copper electrode with an L-shape was manufactured and tested successfully Figure 30.

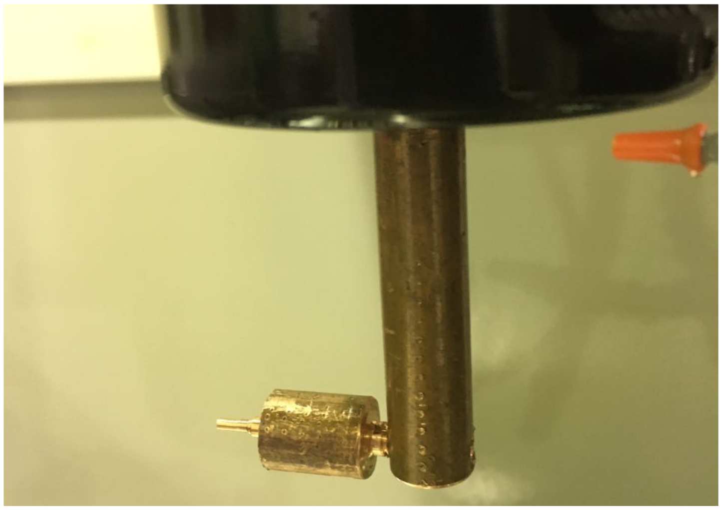


Figure 30: Copper electrode for seeding defects into the bearing

After the trial experiment was successful, this approach was decided to be used throughout this research. For small defects, with diameters less than 2 mm, copper wires were used Figure 31. A stability issue of the wire was observed. This problem usually results in a defect with an irregular shape. Figure 32 a and b show outer and inner ring defected bearings using 2 mm copper electrode and 0.4 mm wire respectively.

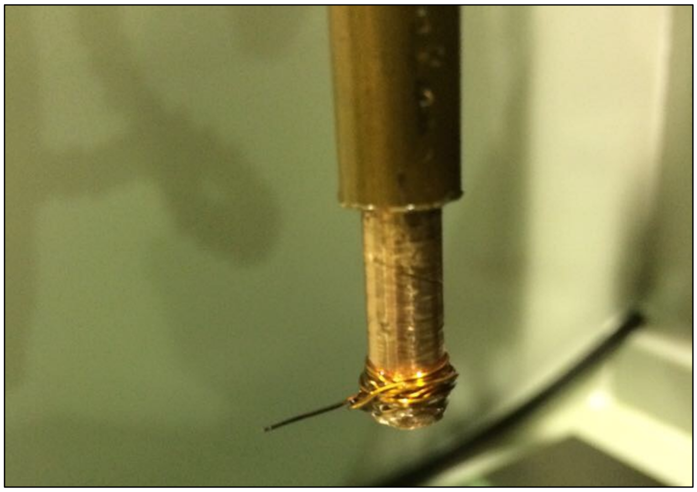
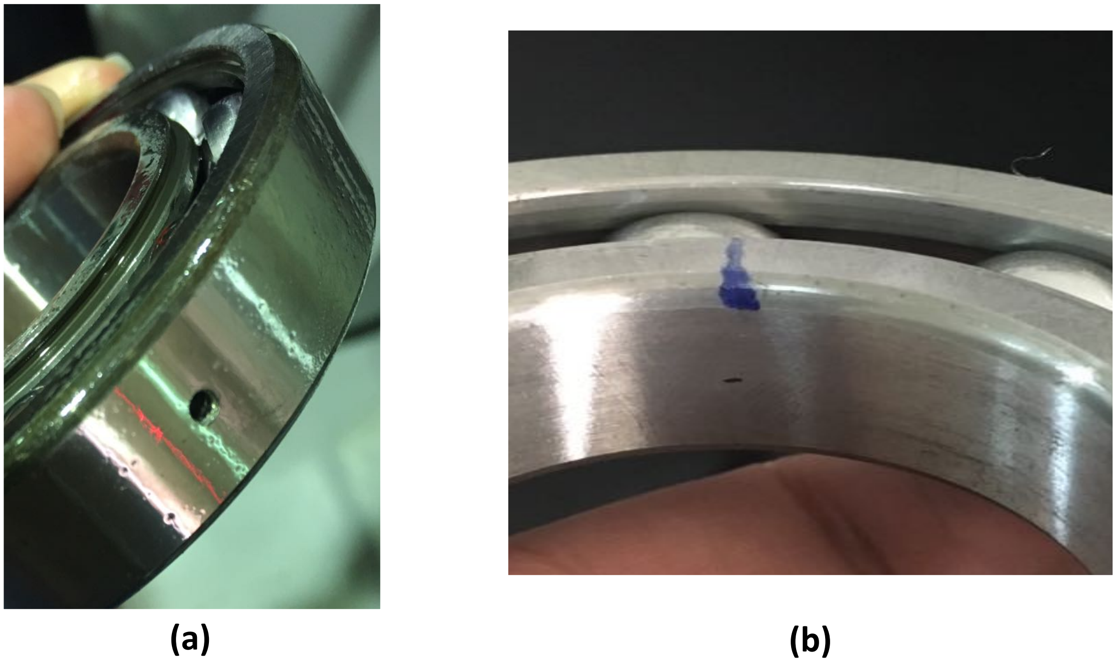


Figure 31: Copper wire used in the EDM



(a) (b)

Figure 32: Bearing defects using EDM (a) 2 mm outer defect, (b) 0.4 mm inner defect

3.2.5 Cleaning and Lubricating the Bearings

When the defects are seeded, the material that was initially filling the defect turns into a powder that may go deep inside, between the moving parts of the bearing. These powder particles can damage the bearing and affect its vibrational response. Therefore, the need for cleaning the bearing raised with crucial priority. The first step of cleaning consisted of immersing the bearing in an Acetone bath Figure 33. During such operation, it is crucial not to rotate the bearing to avoid damaging the surfaces being in contact with the metallic abrasive powder.

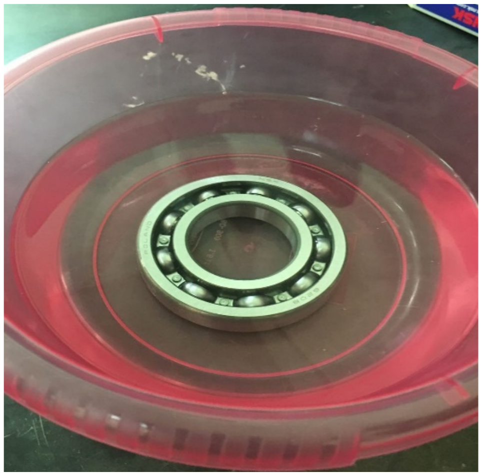


Figure 33: Cleaning of defected bearing in Acetone bath

Once the bearing is correctly cleaned, it needs to be lubricated again by a small amount of oil Figure 34. The same amount and type of lubrication were used for all the used bearings in this experiment. Afterwards, the bearing was slowly rotated by hand to make sure that it rotates smoothly. Finally, all the bearings were tagged,to avoid any confusion between defect sizes and locations.

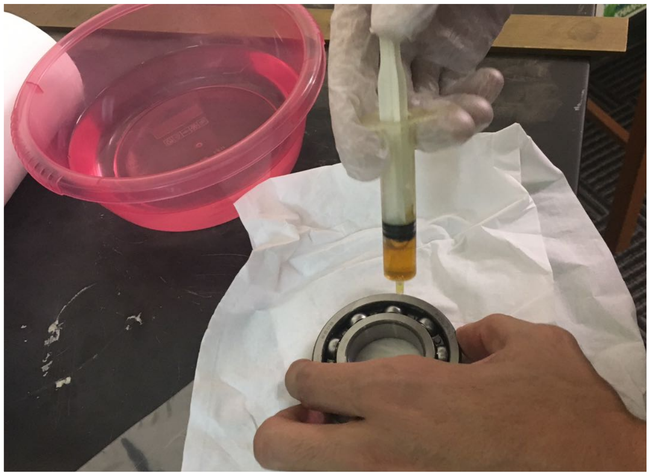


Figure 34: Applying lubricating oil to bearing after cleaning

3.3 Instrumentations (Accelerometer and Data Acquisition)

3.3.1 Vibration Measurement Function

To measure the vibration signal of the bearing an integrated circuit piezoelectric (ICP) accelerometer is used. The accelerometer used in the testing apparatus manufactured by PCB Piezotronics (model no. 352C33, 100mV/g) and directly mounted on the housing of the testing bearing. The analog signal obtained from the accelerometer is conveyed to a data acquisition system by National Instruments (model, DAQ-9174) to convert it to a digital signal. A computer connected to the digital acquisition system, using Matlab, can then manipulate this digital signal. Matlab software will also be used to acquire the accelerometer signals as well as, analyses of this data.

3.3.2 Accelerometer Mounting:

The vibration sensor (accelerometer) should be installed as close as possible to the centerline of the bearing and in the same direction of the load, to avoid picking up distorted signals and minimize the noise. The best location for the sensor is on top of the defected bearing housing Figure 35.

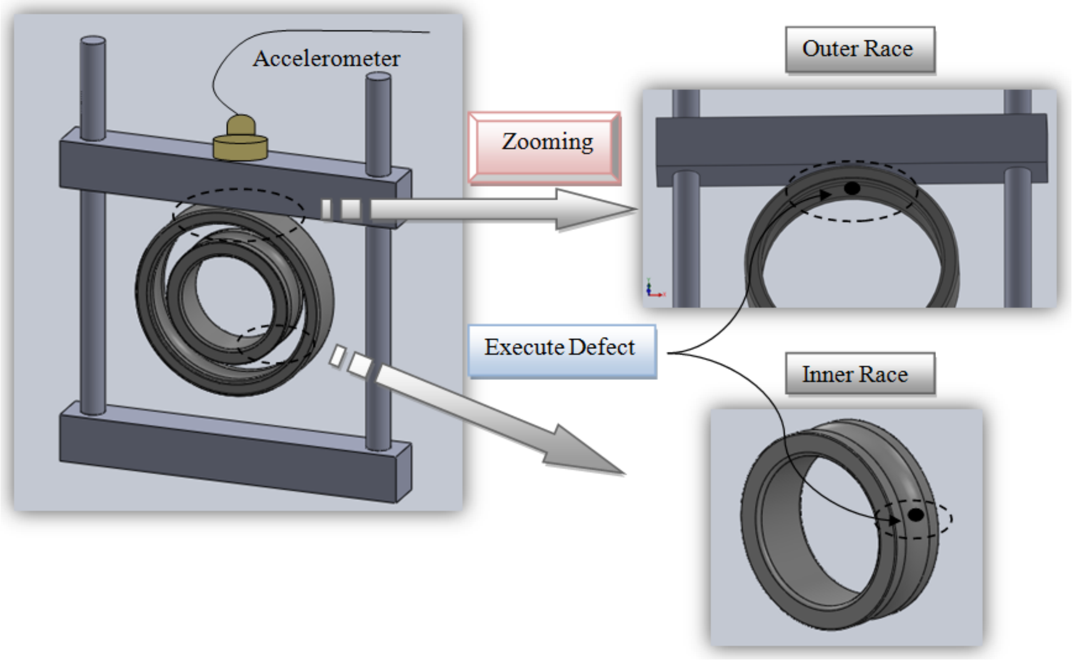


Figure 35: Location of the acceleration sensor

How the accelerometer is mounted on the surface is also important. The accelerometer must be fixed in a firm and stable way onto the vibrating component provided that it will not rock or move independently from its base. Accelerometer which is attached loosely will produce the signals from its own independent vibration and therefore will distort the overall vibration response. In this project, the sensor was screwed by a stud to the upper part of the housing. The final assembly of the system with mounted sensor, data aquision and computer is shown in Figure 36.

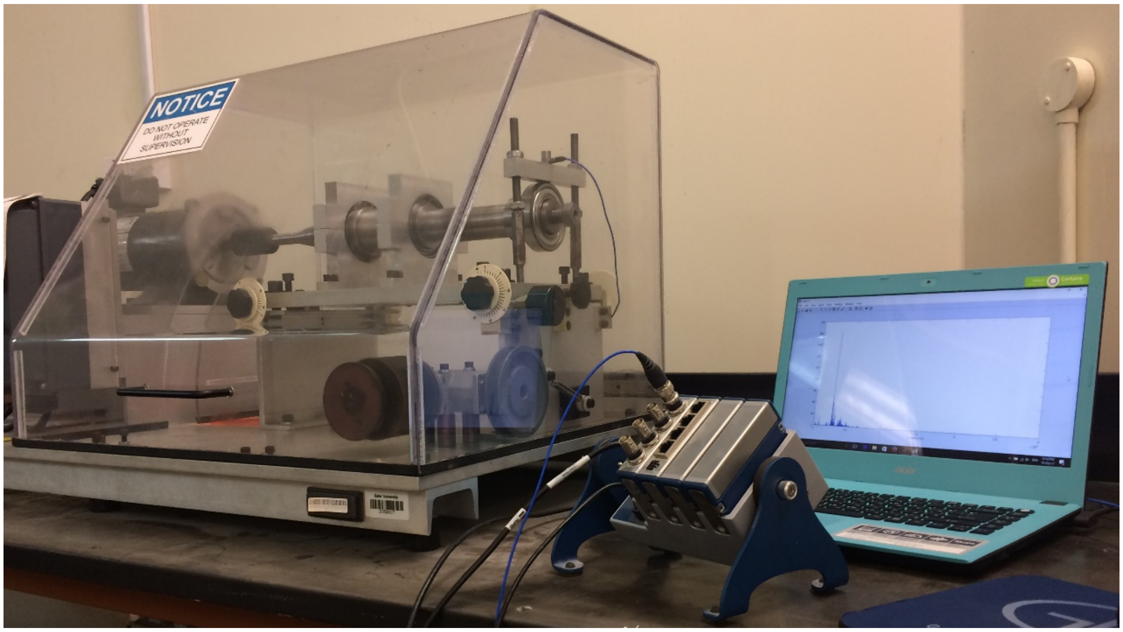


Figure 36: final assembly of the system with mounted sensor, data aquision and computer

3.4 Test Procedures

The test procedure followed while conducting the tests on the bearing with or without a defect was as follows:

- Prepare MatLab code which will be used to acquire the data for a particular test including (bearing name and defect location, duration of the experiment, sampling rate, use new saving file name).
- Make sure the testing bearing is lubricated correctly and ready to be tested (same type and amount of lubricant used in all tests).
- Fix testing bearing correctly, (For the case of outer ring defect the defect should be aligned with applied load direction).
- Mount the accelerometer on its position and check all the wires and connections (sensor and data acquisition).
- Apply a very light load on the testing bearing (the applied load was required just to close the internal clearance of the bearing).
- Put safety cover.
- Check the speed (Fixed).
- Start the experiment.
- Wait for warm-up and steady operation.
- Record **ten** trials for the same bearing.
- Release the load and stop the experiment.

CHAPTER 4 RESULTS AND DISCUSSIONS

In this experiment, the vibration response of healthy bearings, together with damaged bearings (where the defect was added to the outer ring or the inner ring) are examined. For nine bearings, the defects were applied to the inner raceway while for ten other bearings the defects were seeded on the surface of the outer raceway. Three more bearings were kept in their healthy state to serve as references. The sizes of the applied defects were identical for both outer and inner rings. As displayed in Table 4, the defects sizes range from 0.35mm up to 3mm. In the beginning of this experiment the goal was to seed very small defects as small as 0.10 mm. In order to achieve such small defect size, very thin copper wire was used in the EDM, but due to instability of the thin wire and its vibration during defect seeding process, a smaller defects with regular shape couldn't be introduced in bearings and the wires found to be stable from 0.35 mm diameter.

Table 4: Defects sizes on outer and inner rings

Defect Size [mm]	**0.35**	**0.40**	**0.50**	**0.58**	**1.00**	**1.15**	**1.50**	**2.00**	**3.00**
Defect to Ball Ratio	2.9 %	3.4 %	4.2 %	4.9 %	8.4 %	9.7 %	12.6 %	16.8 %	25.2 %

All tested bearings had the same lubrication, mounting and testing conditions. For each tested bearing, the experiment was repeated ten times to increase the reliability of the results (by minimizing their dispersion about their mean values).

In summary, the experiment had three inputs and one output. The inputs were: the defect size of the bearing, the rotational speed of the rotor and the applied load on the tested bearing, whereas the response vibration signal was the output of this experiment. The total number of experiments conducted on twenty-two bearings used in this study accounted for 220 trials overall. Each trial had the duration of ten seconds.

4.1 Raw Data Analysis

To monitor the condition of the bearing (while being installed on the test rig), a variety of techniques and indicators can be used. An indicator of observation is based on the parameter, which can be acquired while the machine is running and must clearly reflect the state and performance of the machine. In addition, the indicator's evolution in time must be indicative of the initiation or the propagation of a defect. The temperature of the housing, oil debris analysis, current analysis, acoustics emissions, and the vibration analysis are possible techniques that can represent the state or the performances of equipment and follow its degradation with time [53, 54].

For this particular research, the technique of vibration signal analysis was used in machine health monitoring as it is one of the most widely used technique in condition-based maintenance [13, 48, 59].

4.2 Time Domain Analysis

Time domain technique is considered to be the easiest and simplest technique to analyze the vibration signal. Other techniques may usually require more technical skills and mathematical background. This easy technique can pinpoint the existence of defects inside bearings but, unfortunately, does not give information about the location of the defecte.g. inner race, outer race, cage or the rolling element. However, the evolution with time is meaningful of the occurrence or the propagation of a defect.

To investigate or track the effect of increasing defect sizes on the bearing vibration response, several statistical parameters, extracted from the time-domain, are reported in the literature [59]**.** The statistical scalar parameters used in this study are defined and summarised previously in Table 2.

For each one of the 22 bearings considered in this investigation (with and without defect), a Matlab code was written to use the experimental information transmitted to the computer from the sensor, to compute the previous list of parameters and to draw the evolution with respect to the size of defects. In all of the following graphs, these reference values are denoted as the values corresponding to the healthy case, where the defect sized is equal to 0 mm in diameter (i.e., “no defect”).

4.2.1 Temperature Effect on Readings

Initially, there was a problem with repeatability of the collected data. A dispersion of time domain indicators with time was observed. The reason for observed scattering of data was unclear in the beginning, thus a further investigation was performed to explain this issue. After some trials we noticed an increase in temperature of the left supported bearing. Thermal camera was used to visualize the raise in temperature

Figure 37. To study the effect of temperature on the collected data, the machine was operated for definite period of time (70 minutes) and data was collected every five minutes, as shown in Figure 38. It was clear that unrepeatable data problem was originally related with the rise of temperature, since the range of variation of impulse factor data increased with temperature. Therefore, a definite interval of time was kept

between every dataset collection to make sure the temperature did not affect the collected data and avoid the related inconsistencies in it.

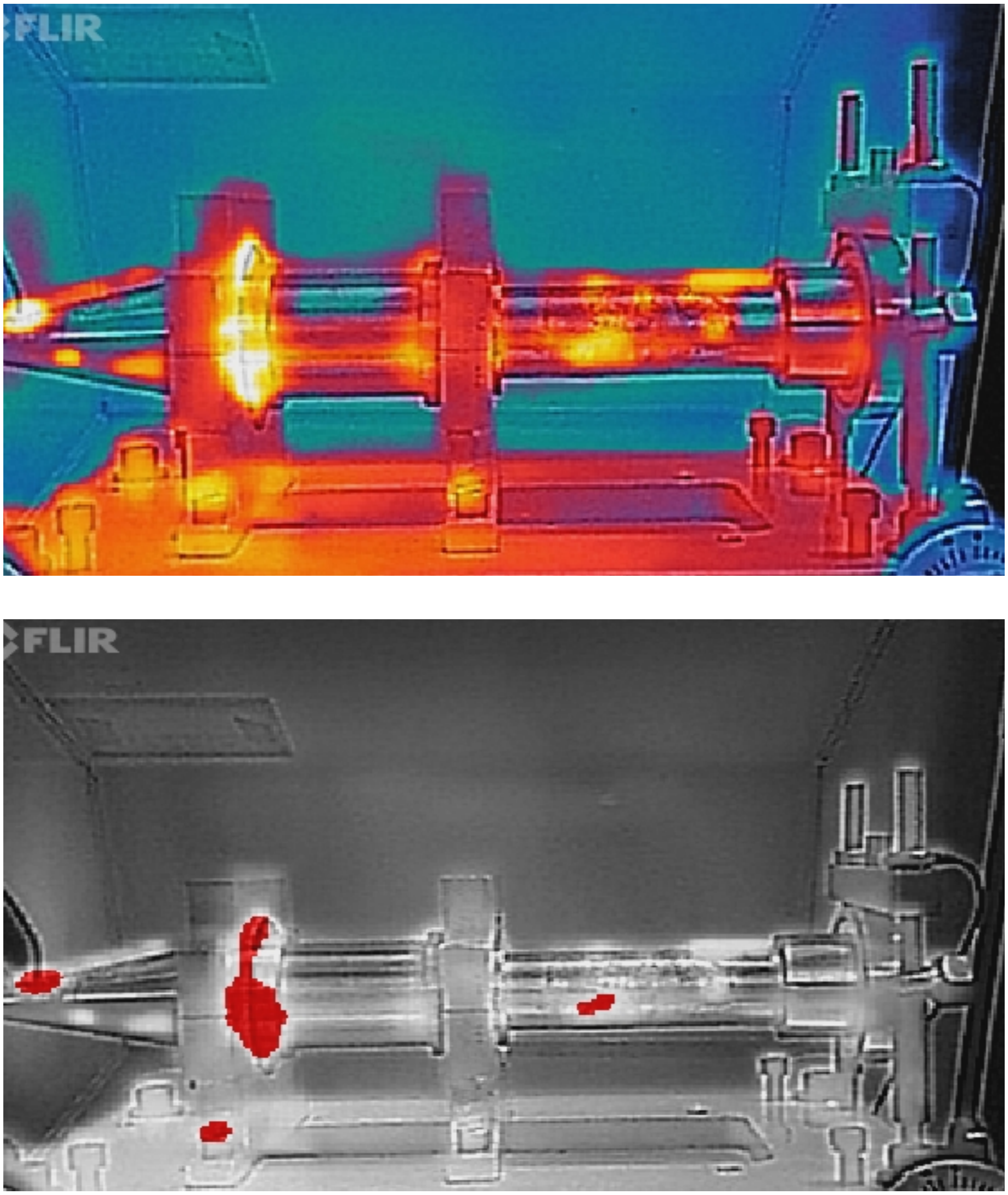


Figure 37: Effect of temperature on the test-rig

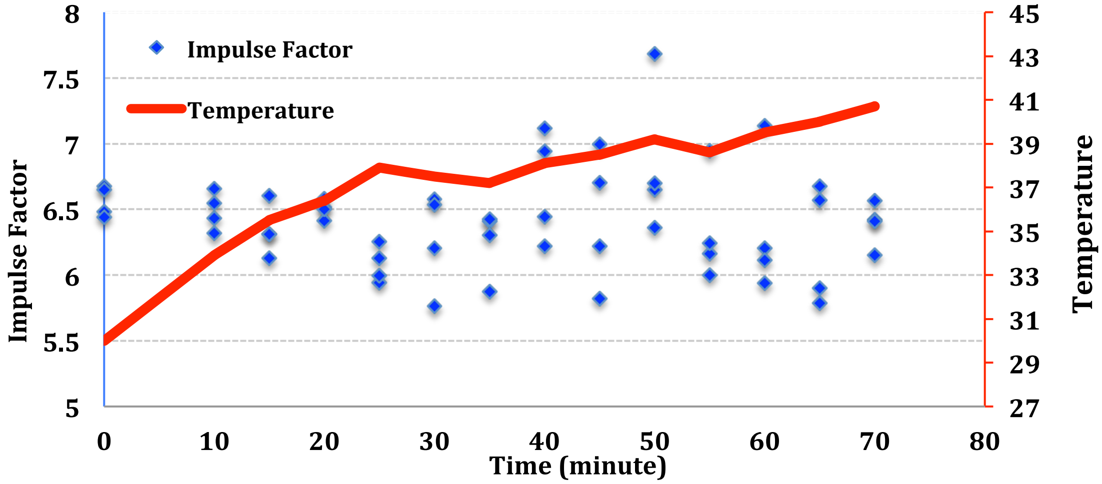
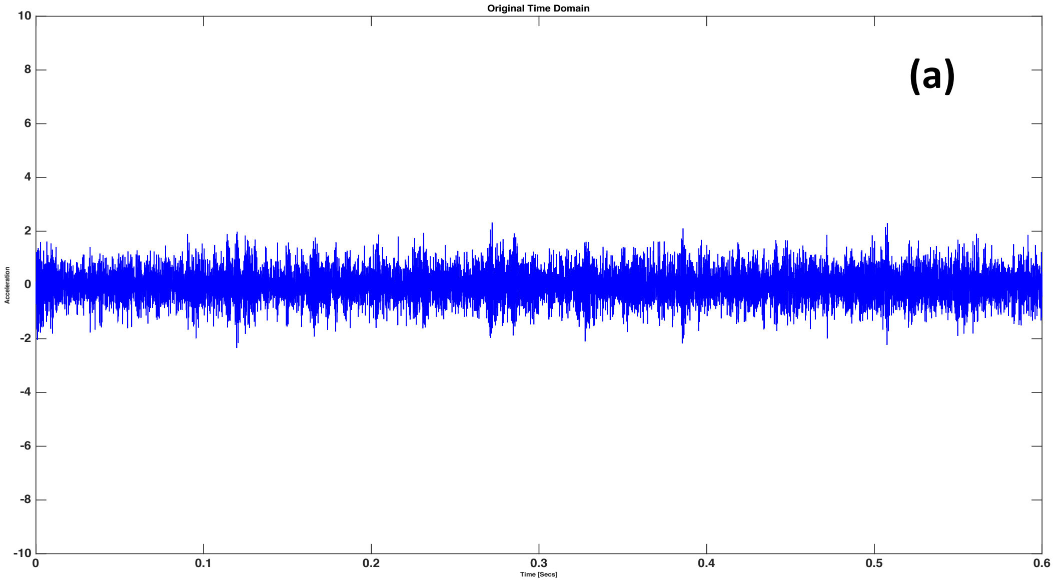


Figure 38: Temperature effect on time domain parameters (impulse factor)

It can be seen that in both cases of outer and inner defects, all of the time domain indicators are increasing along with the defect size for the range of defects used, 0.35 mm to 3 mm. Also, it is seems that for most of the indicators, the evolution follows a second-order trendline. In particular, when the defect gets larger the rate of increase gets higher. For the smaller defects (from 0.35 to 0.58 mm), one can see that there was a fluctuation in the parameter values. This can be due to two facts:

- Imperfection in the fault geometry and size, due to the instability of the EDM electrode (thin wires in this case) during the manufacturing process. This fact was clearly noticed by all technicians involved in the manufacturing process.
- At the early stage of degradation, the signal generated by the bearing is unable to compete with other signals coming from other parts of the machine (especially the

electric problems that were found to be harsh for the readings and also affect the entire spectrum of the frequency-domain). Figure 39 below shows the time domain signal of reference bearing, inner ring and outer ring defected bearing.



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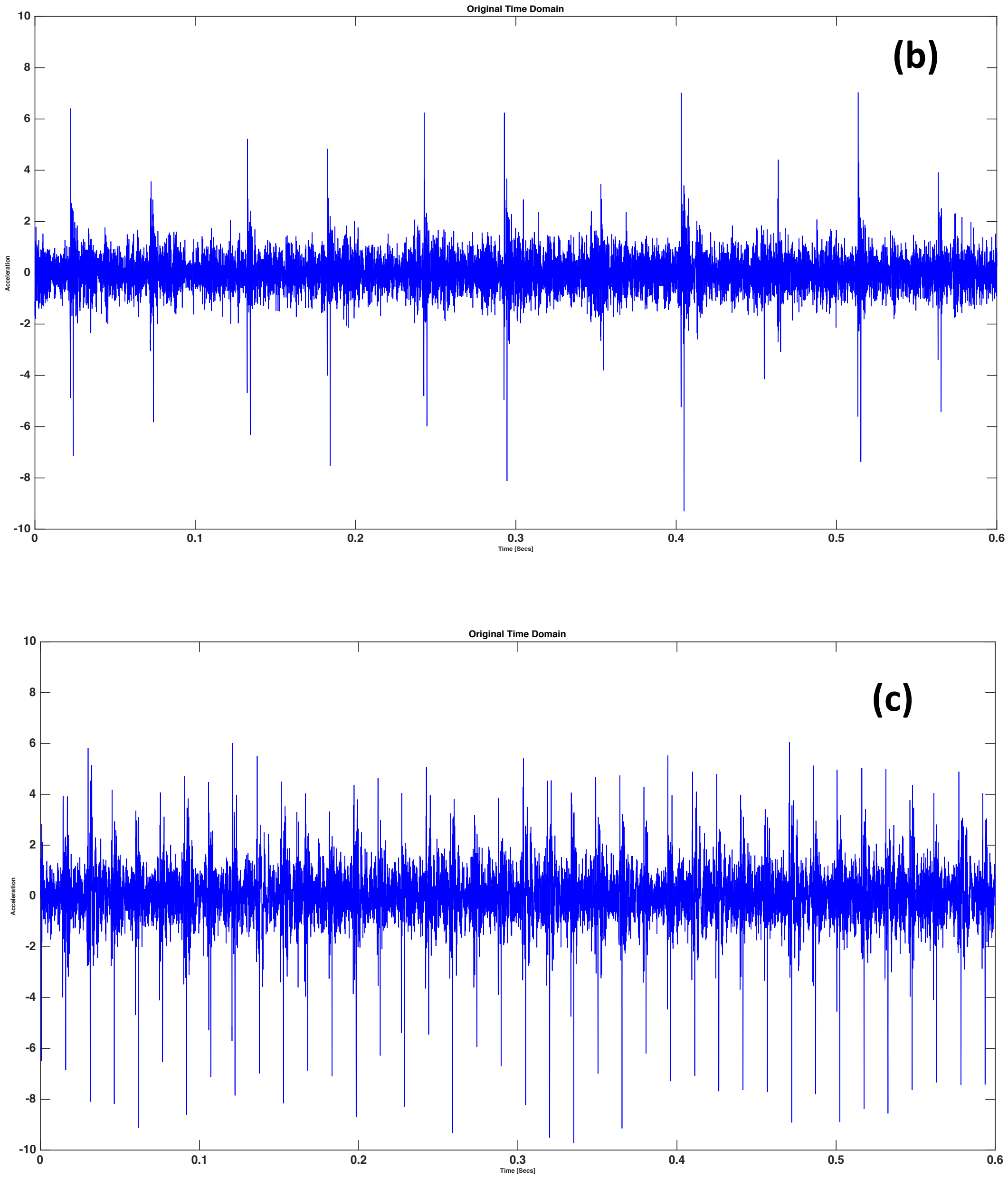
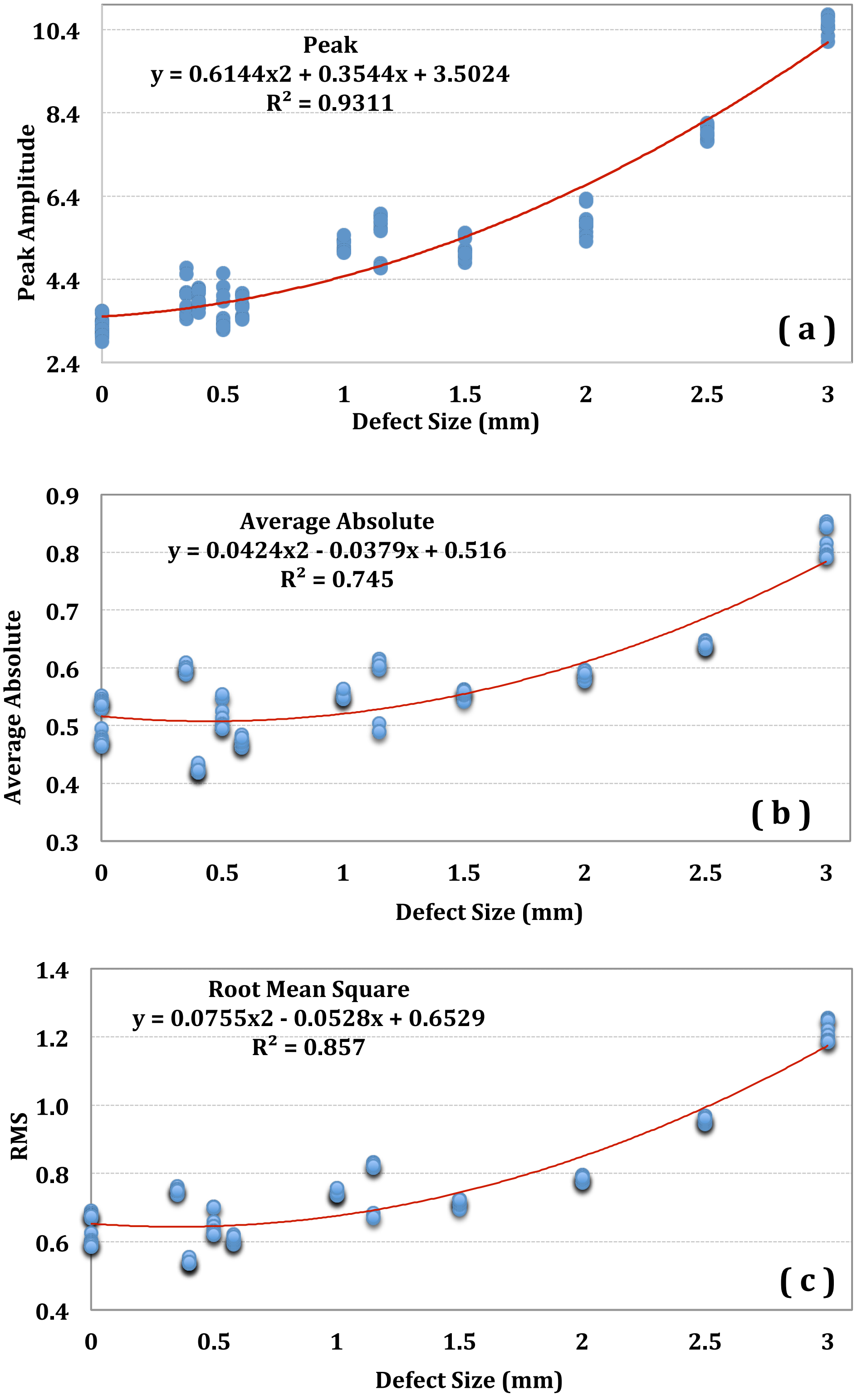
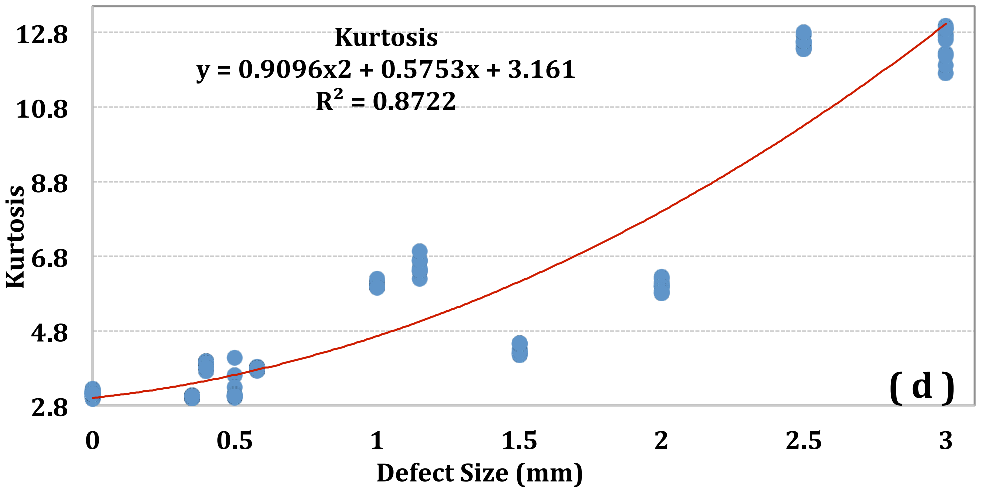


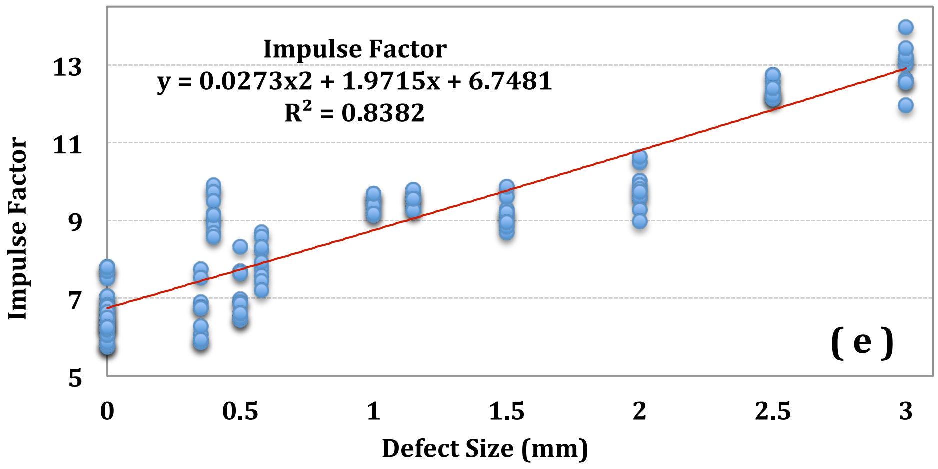
Figure 39: Time domain signal: (a) Reference bearing. (b) Inner ring defected bearing, (c) Outer ring defected bearing

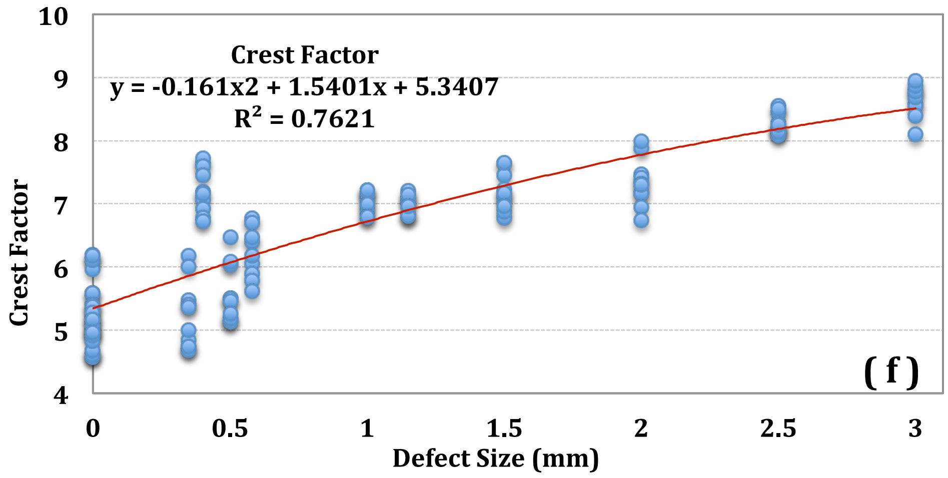
The results of defects located on **Outer Races** are summarized in the following graphs Figure 40.


Peak
y = 0.6144x2 + 0.3544x + 3.5024
R² = 0.9311
Peak Amplitude
10.4
8.4
6.4
4.4
2.4
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(a)
Average Absolute
y = 0.0424x2 - 0.0379x + 0.516
R² = 0.745
Average Absolute
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(b)
Root Mean Square
y = 0.0755x2 - 0.0528x + 0.6529
R² = 0.857
RMS
1.4
1.2
1.0
0.8
0.6
0.4
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(c)

*continued


Kurtosis
y = 0.9096x2 + 0.5753x + 3.161
R² = 0.8722
Kurtosis
12.8
10.8
8.8
6.8
4.8
2.8
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(d)


Impulse Factor
y = 0.0273x2 + 1.9715x + 6.7481
R² = 0.8382
Impulse Factor
13
11
9
7
5
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(e)


Crest Factor
y = -0.161x2 + 1.5401x + 5.3407
R² = 0.7621
Crest Factor
10
9
8
7
6
5
4
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(f)

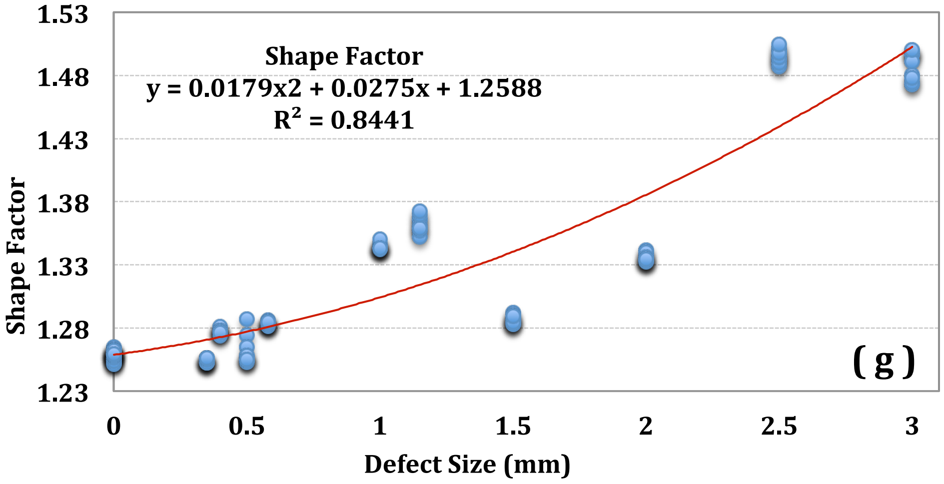
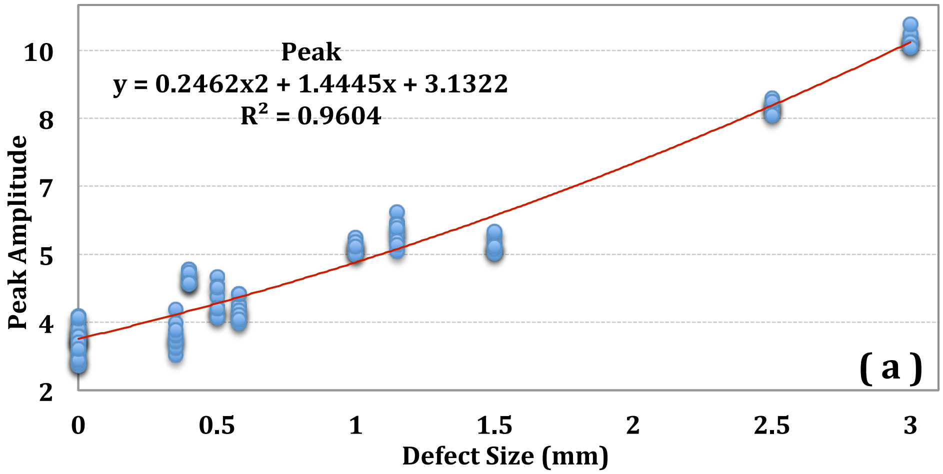


Figure 40: Evolution of Time-Domain statistical parameters versus defect size, located on **Outer ring**: (a) Peak Amplitude, (b) Average Absolute Amplitude, (c) RMS, (d) Kurtosis, (e) Impulse Factor, (f) Crest Factor, (g) Shape Factor

The results of defects located on **Inner Races** are summarized in the following graphs

Figure 41.



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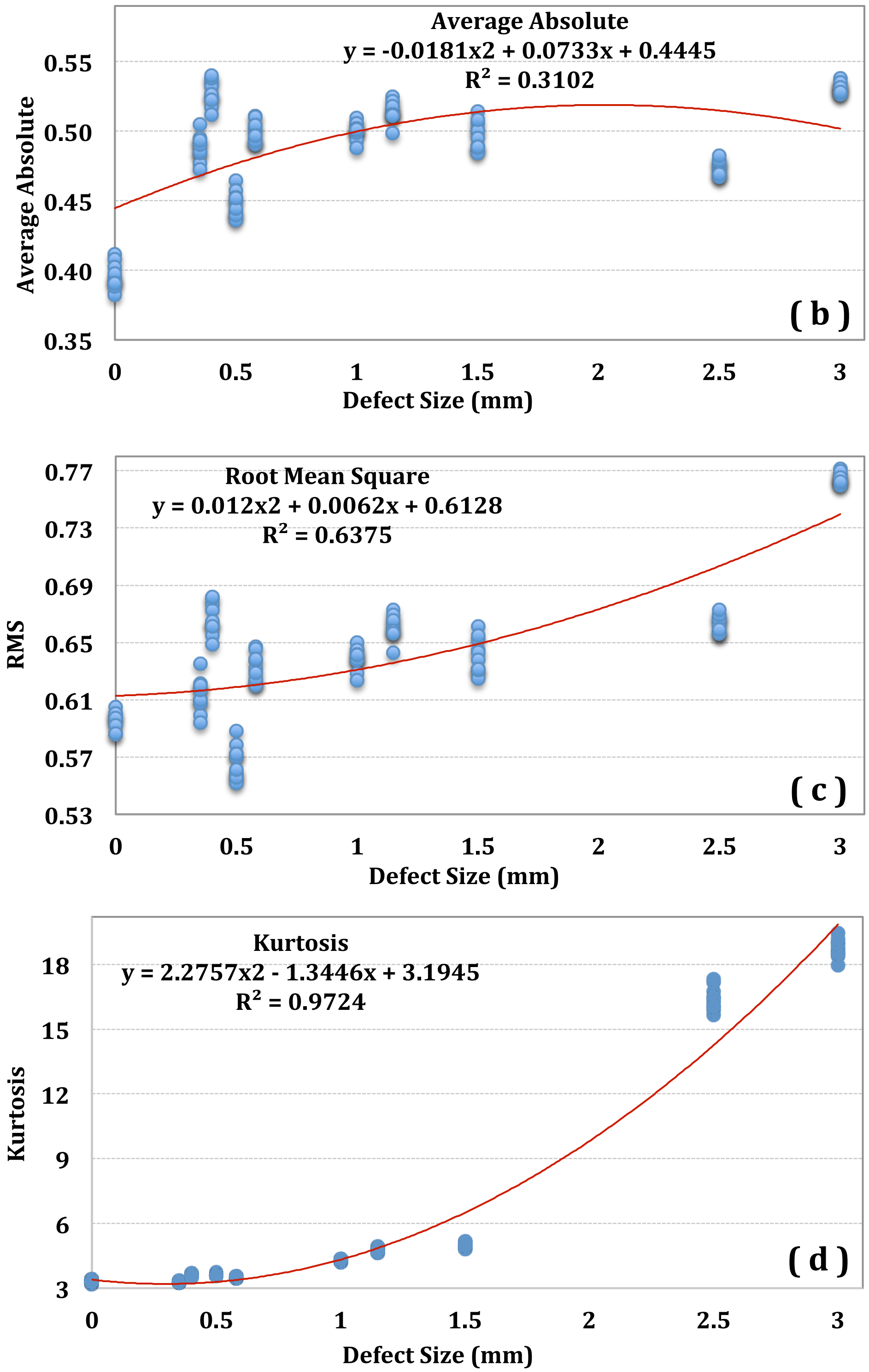
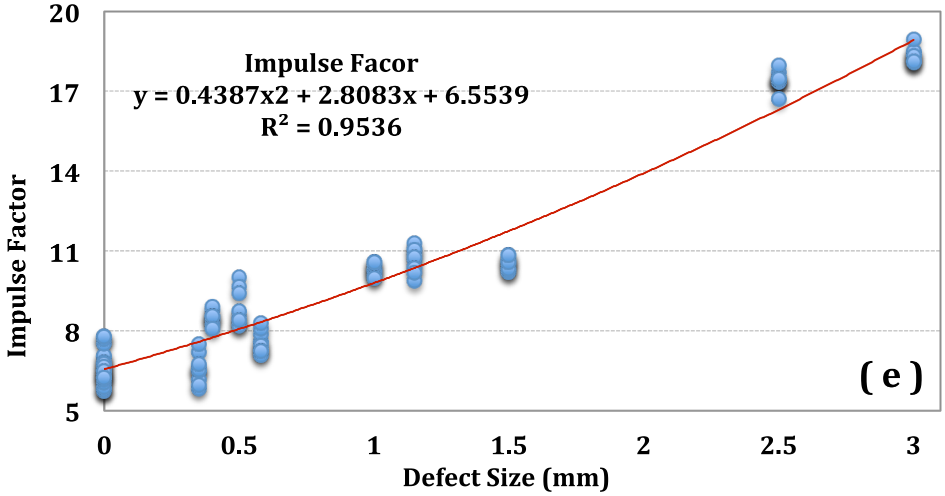
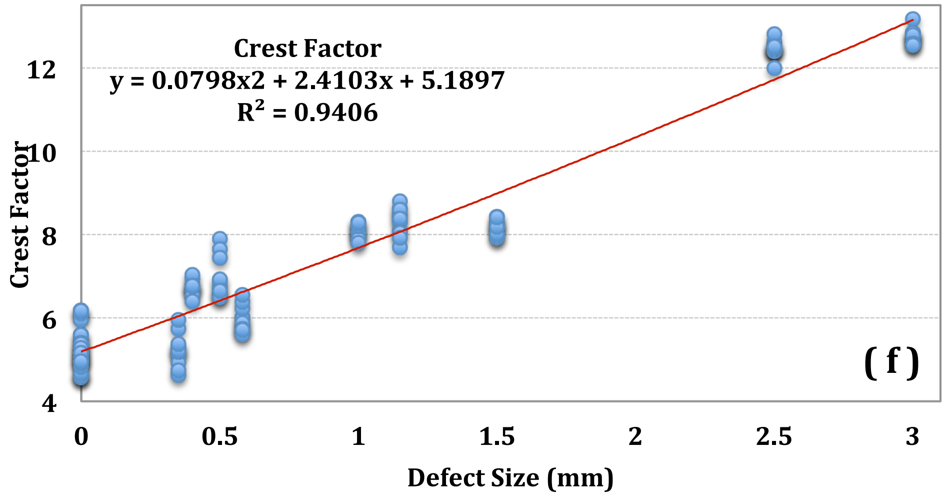

Average Absolute
y = -0.0181x2 + 0.0733x + 0.4445
R² = 0.3102
Average Absolute
0.35
0.40
0.45
0.50
0.55
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(b)
Root Mean Square
y = 0.012x2 + 0.0062x + 0.6128
R² = 0.6375
RMS
0.53
0.57
0.61
0.65
0.69
0.73
0.77
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(c)
Kurtosis
y = 2.2757x2 - 1.3446x + 3.1945
R² = 0.9724
Kurtosis
3
6
9
12
15
18
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(d)

*continued


Impulse Facor
y = 0.4387x2 + 2.8083x + 6.5539
R² = 0.9536
Impulse Factor
20
17
14
11
8
5
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(e)


Crest Factor
y = 0.0798x2 + 2.4103x + 5.1897
R² = 0.9406
Crest Factor
12
10
8
6
4
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
(f)

*continued

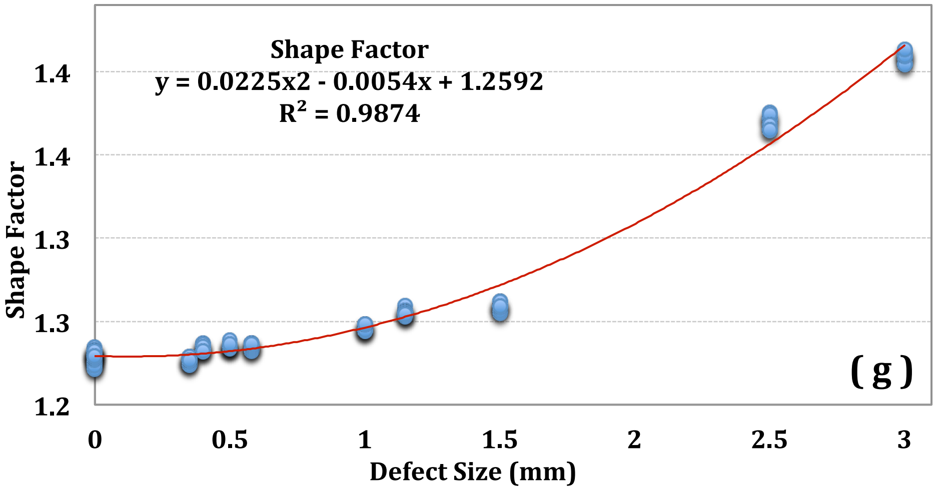


Figure 41: Evolution of Time-Domain statistical parameters versus defect size, located on **Inner ring**: (a) Peak Amplitude, (b) Average Absolute Amplitude, (c) RMS, (d) Kurtosis, (e) Impulse Factor, (f) Crest Factor, (g) Shape Factor

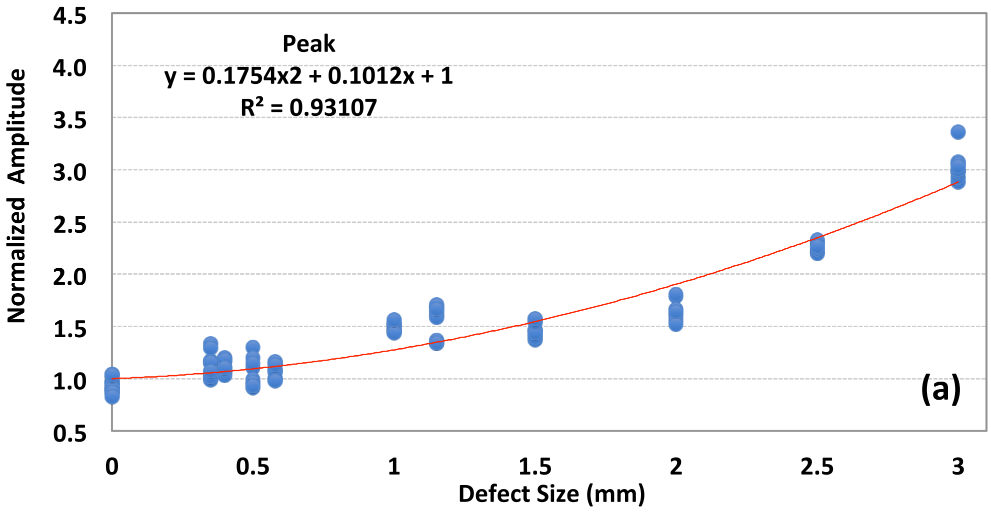
From the analysis of the graphs displayed above, several conclusions could be drawn:

1. All the statistical parameters, extracted from the time-domain, are sensitive to the increase of localized defects, but with different extents. As a fair approximation, the increase was found to follow a parabolic curve of the second degree.
2. For each set of points obtained from a particular defect, different dispertions are observed for the statistical parameters, around their mean values.
3. Similarly, the location of the mean values with respect to the trendlines are different from one parameter to another.
4. In the case of healthy bearings, the Kurtosis values were found to be about 3, which is in perfect match with other results previously published [60].

5. For the sake of comparison between sensitivity degrees of the parameters, the locations of the starting and ending points are essentials, since they define the range of variations. However, because the curves are starting from different values, their mutual comparisons are somehow difficult to achieve.

4.2.2 Normalized Time Domain Indicators

Even though the actual values of the different health indicators are meaningful, their degrees of changes are much more important. Therefore, to make the direct comparison of the trend of each indicator, their values should be divided by their initial values (obtained from the reference or healthy bearings). Consequently, on all the graphs, the parameters will start at an initial value of 1. This process is known as "normalization" and allows for better comparison between the evolutions of the parameters. The normalized graphs are shown below in Figure 42 and Figure 43.



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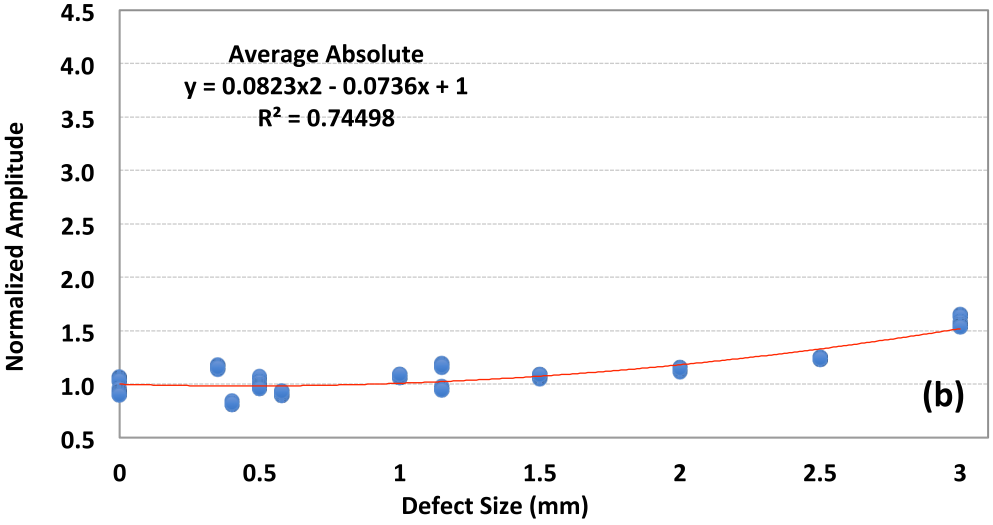
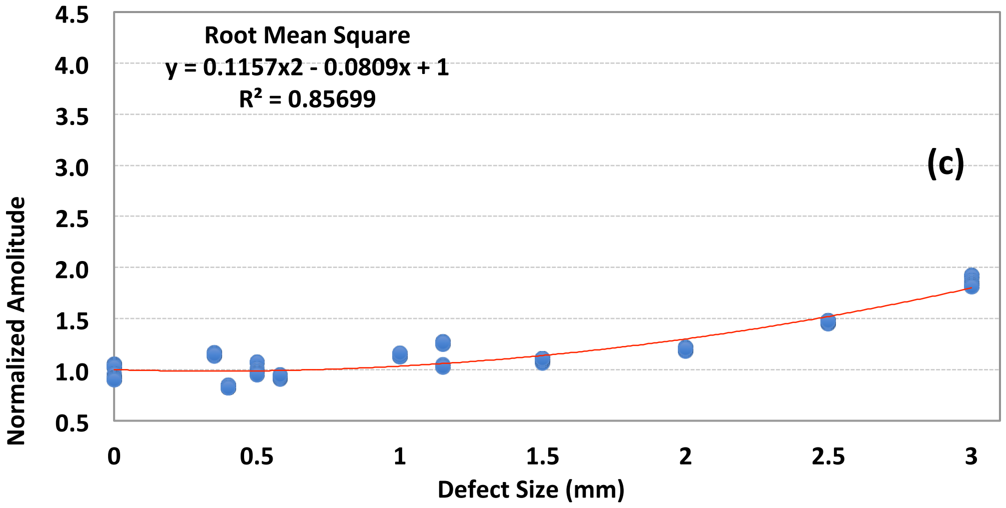
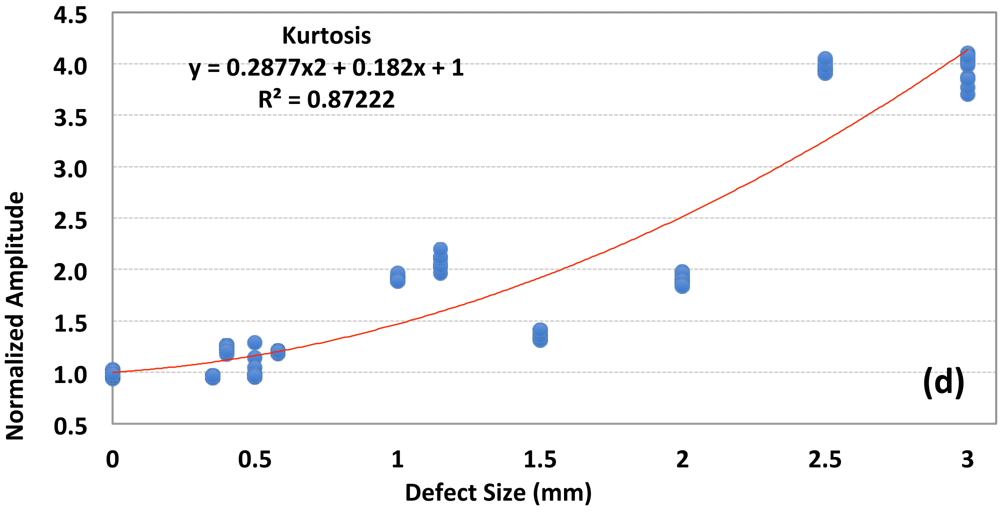


Average Absolute
y = 0.0823x2 - 0.0736x + 1
R² = 0.74498
(b)
Normalized Amplitude
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)



Root Mean Square
y = 0.1157x2 - 0.0809x + 1
R² = 0.85699
(c)
Normalized Amolitude
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)



Kurtosis
y = 0.2877x2 + 0.182x + 1
R² = 0.87222
(d)
Normalized Amplitude
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)

*continued

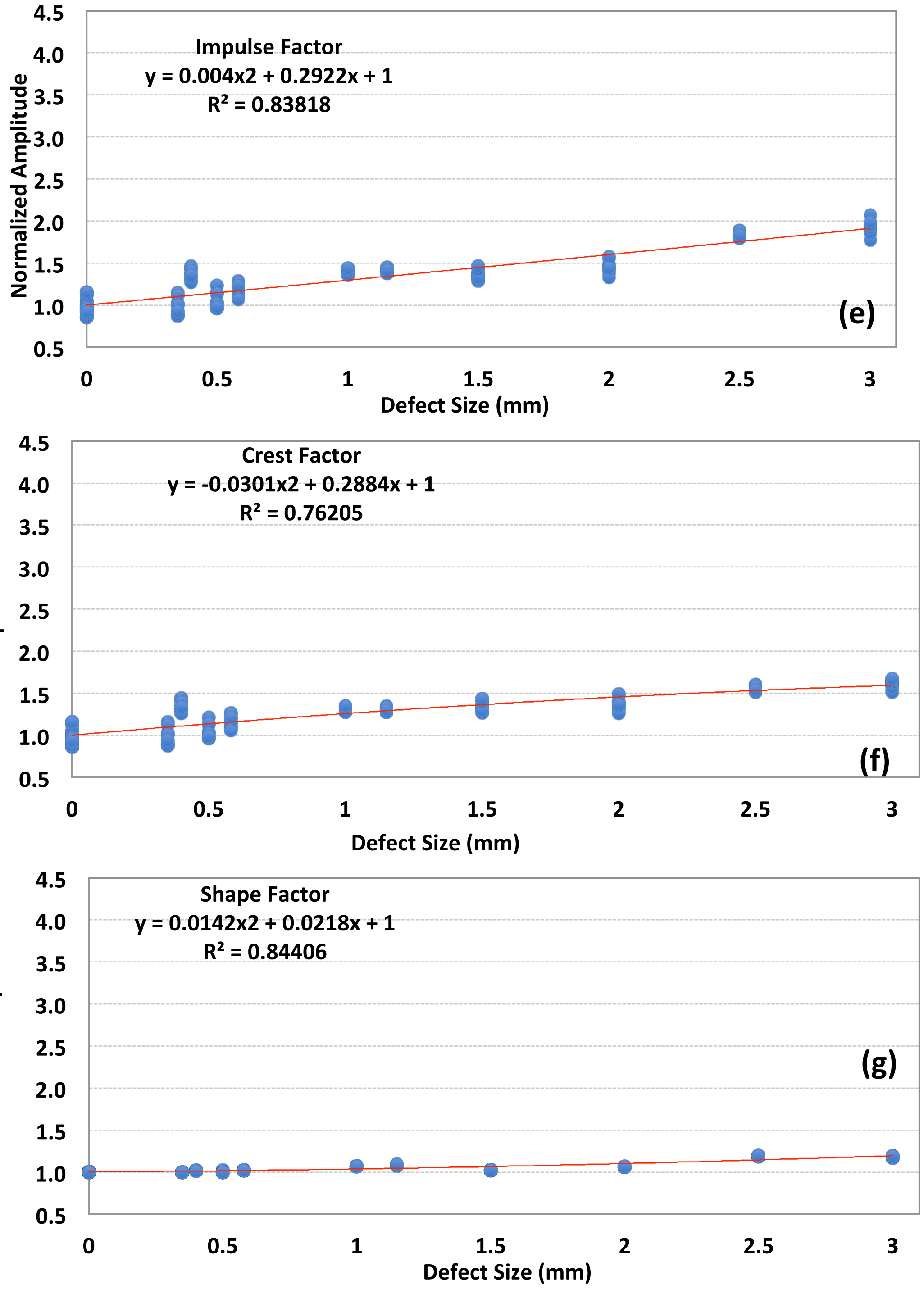
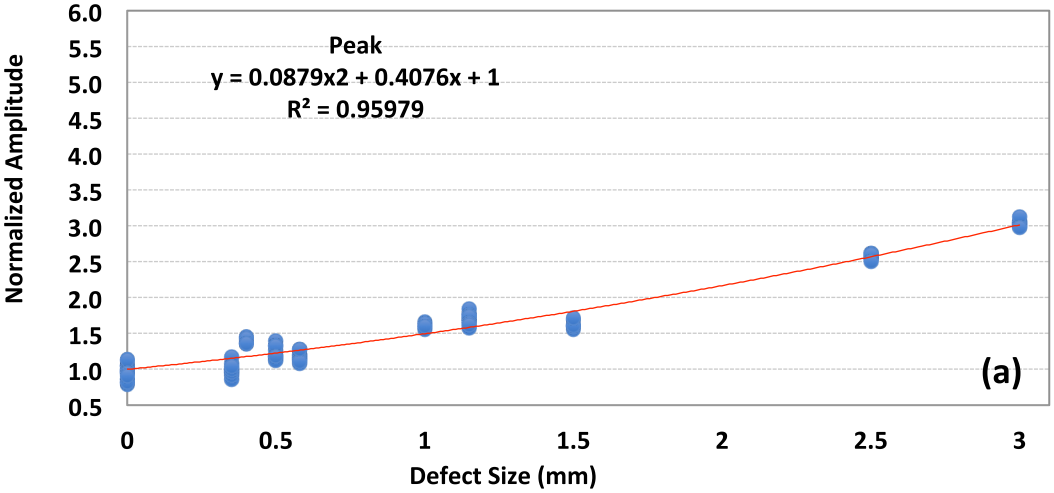
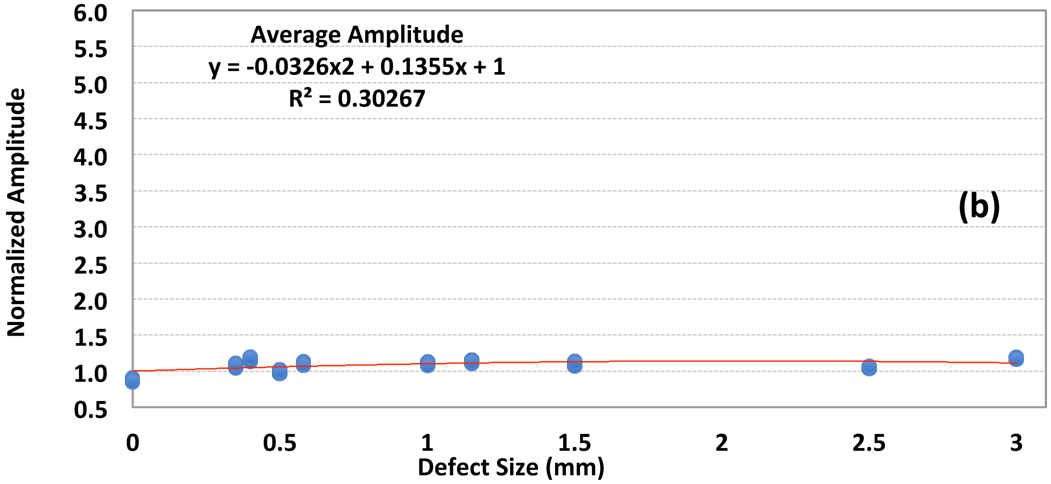


Figure 42: Evolution of **normalized** Time-Domain statistical parameters with defect size, located on **Outer ring**: (a) Peak Amplitude, (b) Average Absolute Amplitude, (c) RMS, (d) Kurtosis, (e) Impulse Factor, (f) Crest Factor, (g) Shape Factor

The results of normalized time domain indicators with defects located on **Inner Races** are summarized in the following graphs.





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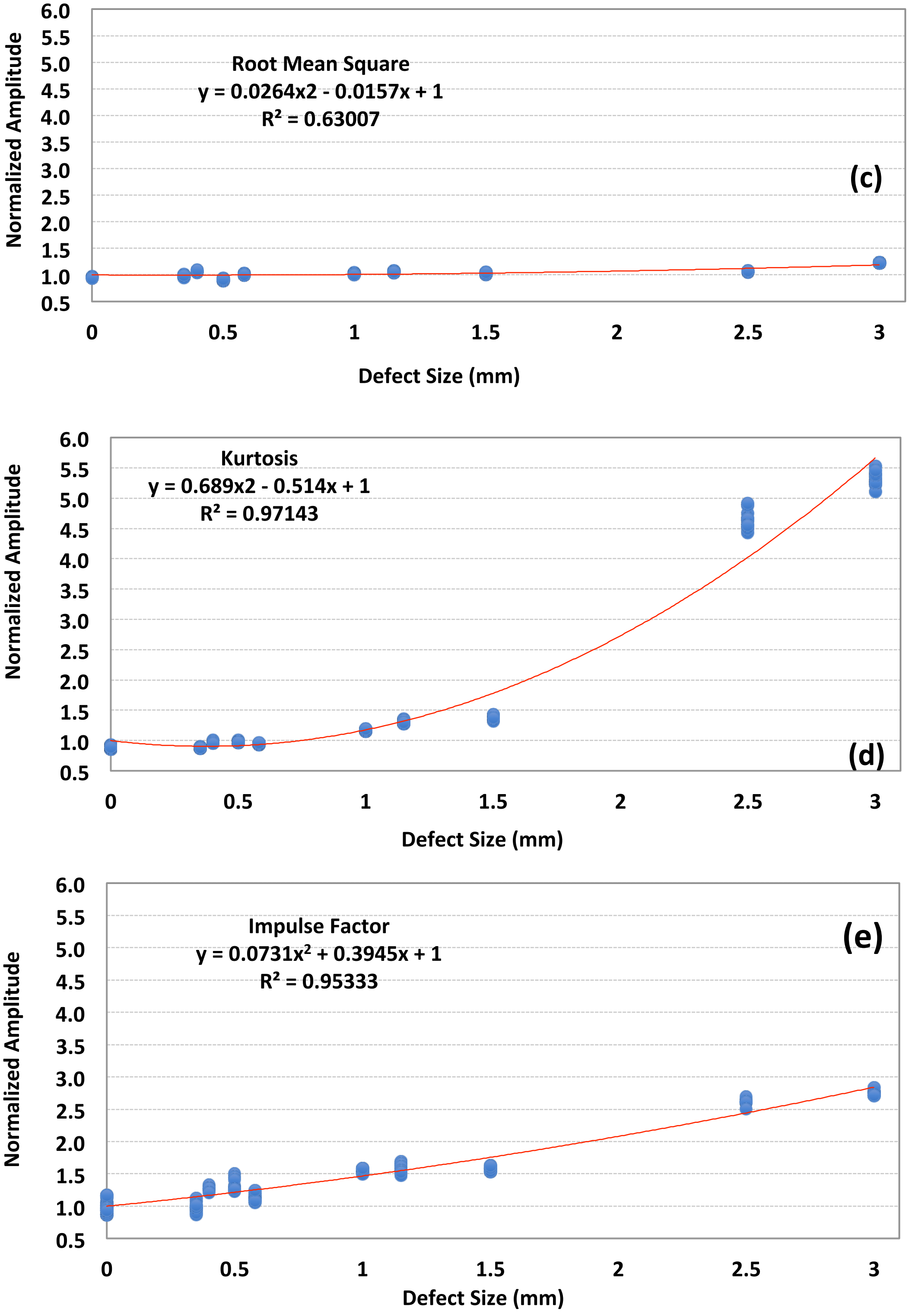

Root Mean Square
y = 0.0264x2 - 0.0157x + 1
R² = 0.63007
(c)
Normalized Amplitude
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)
Kurtosis
y = 0.689x2 - 0.514x + 1
R² = 0.97143
(d)
Normalized Amplitude
Defect Size (mm)
Impulse Factor
y = 0.0731x² + 0.3945x + 1
R² = 0.95333
(e)
Normalized Amplitude
Defect Size (mm)

*continued

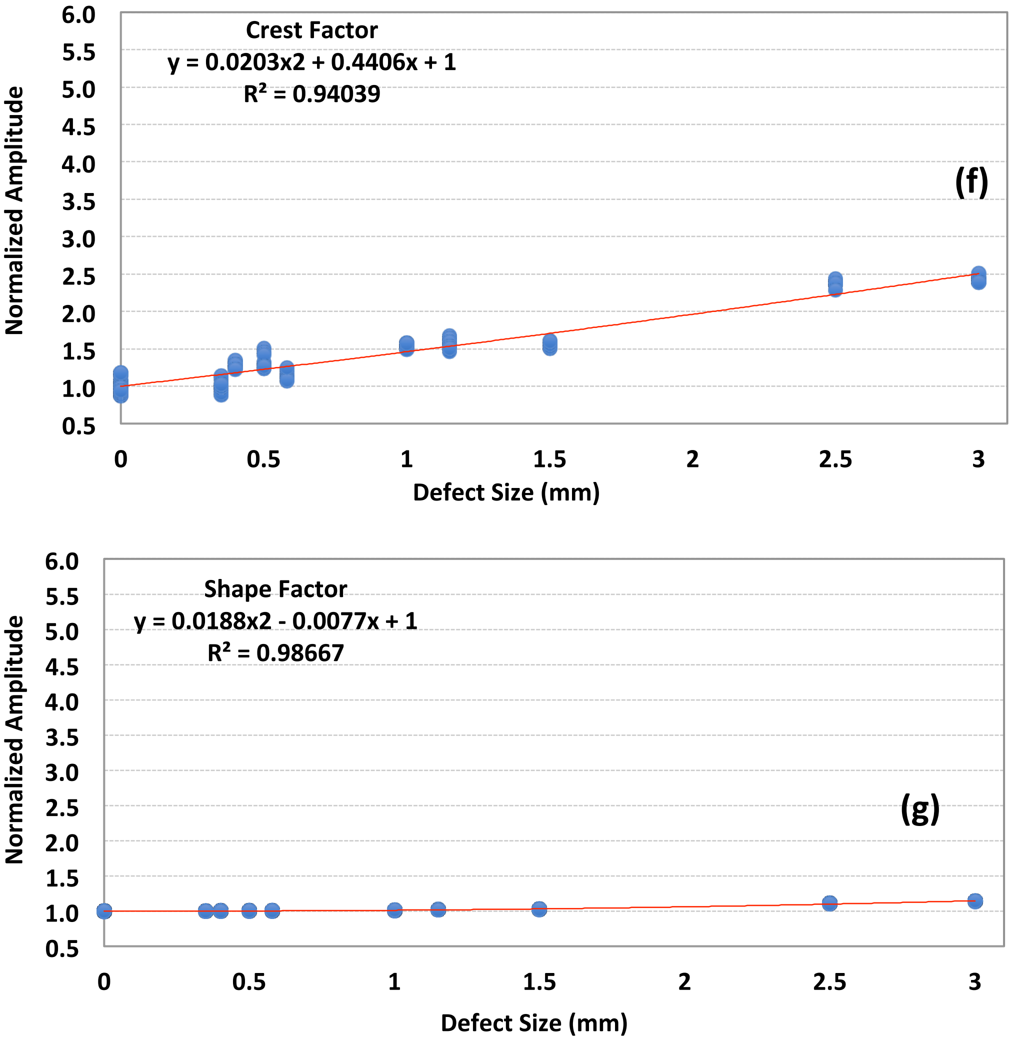


Figure 43: Evolution of **Normalized** Time-Domain statistical parameters with defect size, located on **Inner ring**: (a) Peak Amplitude, (b) Average Absolute Amplitude, (c) RMS, (d) Kurtosis, (e) Impulse Factor, (f) Crest Factor, (g) Shape Factor

4.2.3 Comparison Between Inner and Outer Rings Defects

At first glance to the previous normalized curves, one can see that the Shape Factor (SF) is a parameter with very low sensitivity to bearings damage evolution, regardless of the defect location on the outer race or inner race. This result is in perfect match with [59]. For that reason; SF will be permanently omitted from the list of statistical parameters to be considered in this investigation. As portrayed in Figure 44 and Figure 45 below, the kurtosis appears as the most sensitive time-domain parameter to the increase of defect size, regardless of the defect location, on outer race or inner race.

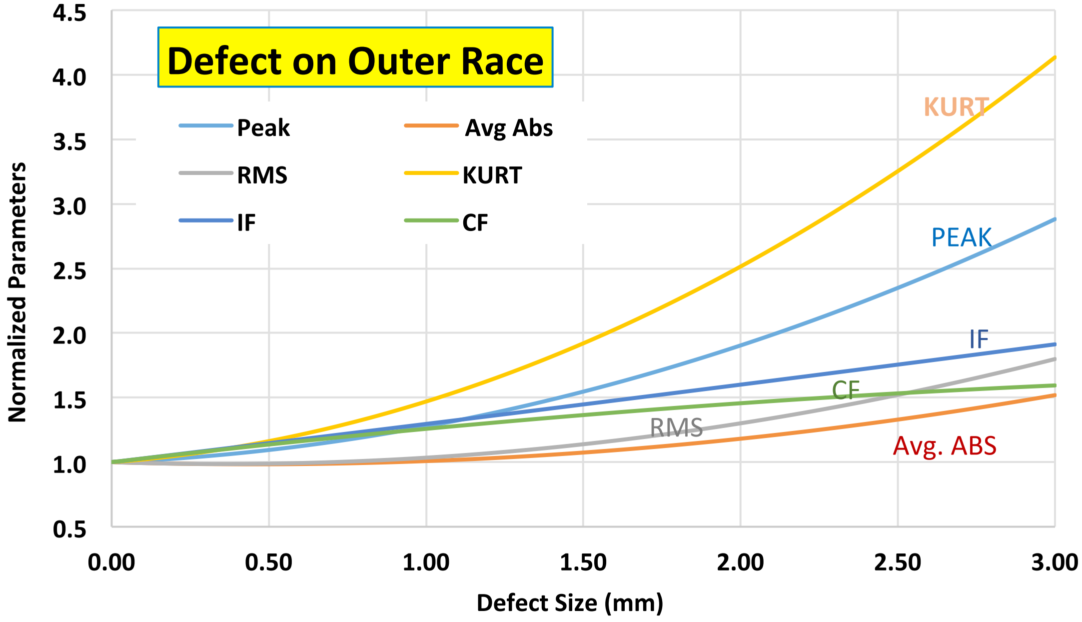


Figure 44: Combined time domain parameters of **Outer ring** defected bearings

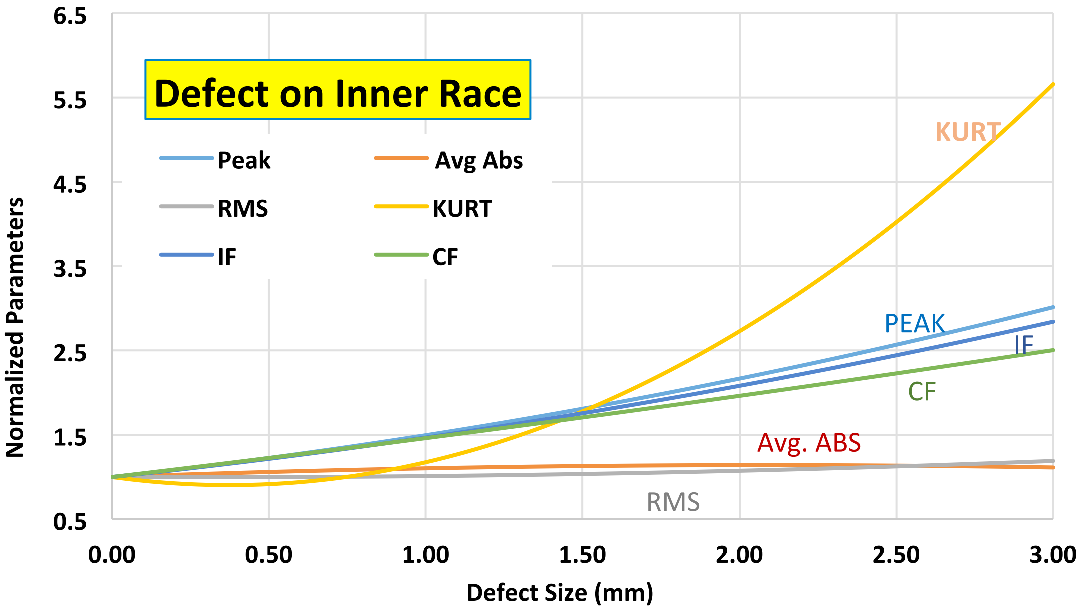
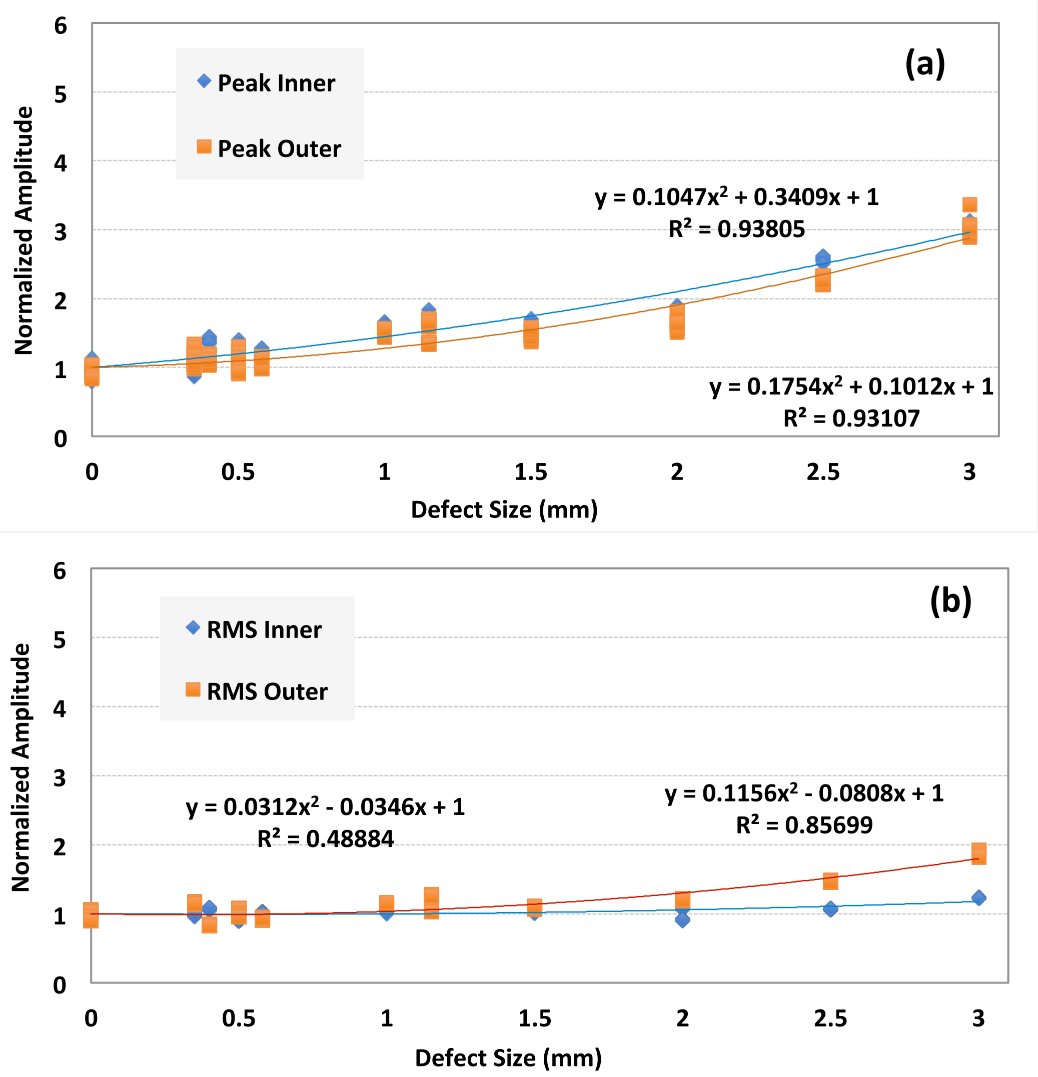


Figure 45: Combined time domain parameters of **Inner ring** defected bearings

When the comparison is relating the two cases of outer-race defects and inner-race defects, the extracted parameters have similar degrees of sensitivity, contrarily to what was previously expected. Usually, when the defect is located on the outer race, the sensitivity of the time-domain extracted parameters is higher in that case. This is probably due to two main facts:

- The path from the defect to the sensor is shorter, in the case of a defect located on the outer race.
- When the defect is located on the outer race, and this outer race is fixed, the defect remains longer time inside the load zone. Contrarily, when the defect is located on a rotating inner race, the defect will cross the load zone once every cycle and during a short time.

In this research, no significant difference was found between the outer race and inner race cases Figure 46. This is probably because the applied load was not very high to magnify the effects of the outer race defects. As a matter of fact, the radial load was only enough to close the internal bearing clearance and prevent the rotation of the outer ring.



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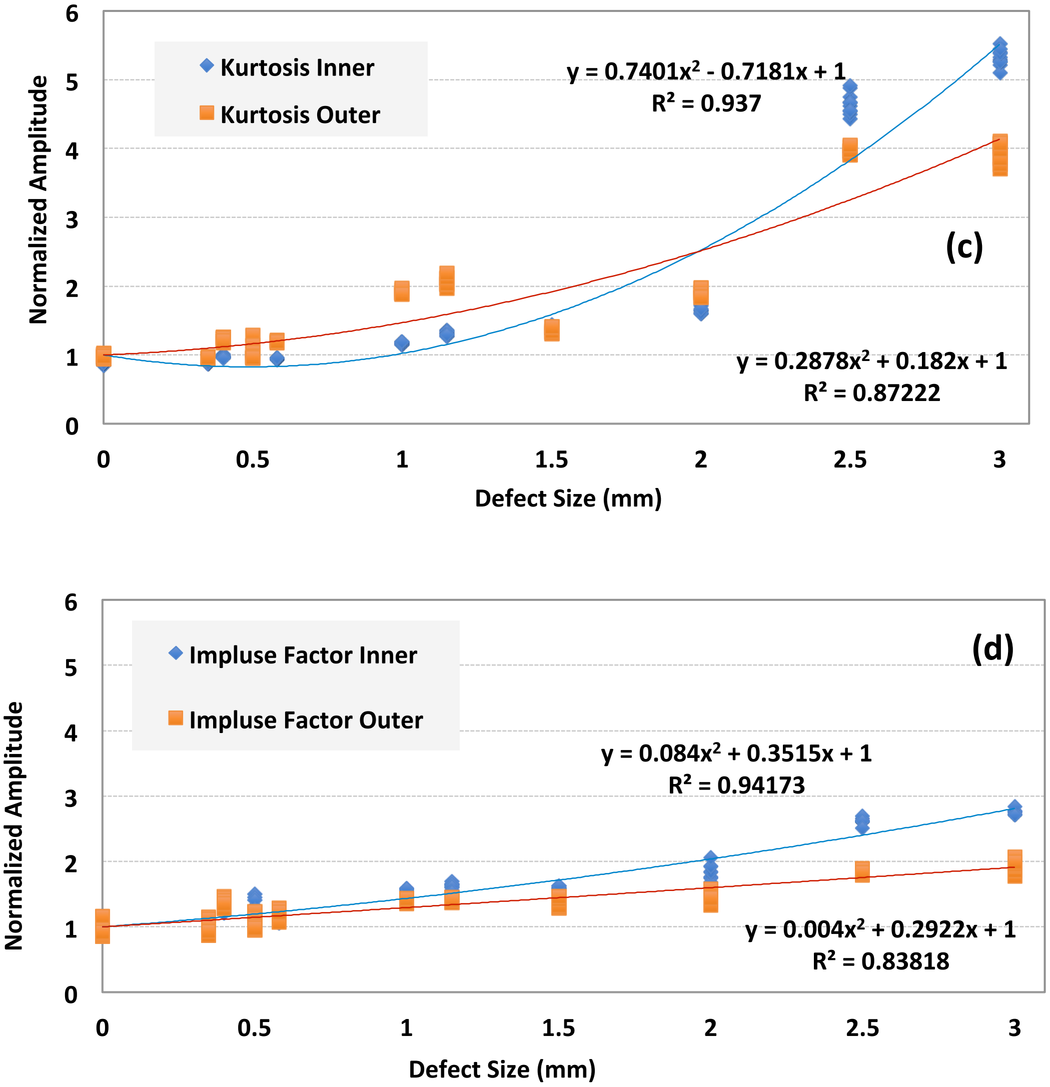


Figure 46: Comparison between time domain parameters for outer race and inner races defected bearings: (a) Peak Amplitude, (b) RMS (c) Kurtosis, (d) Impulse Factor

In the health condition monitoring of any machine, the RMS is usually a very important parameter to consider, since it is directly related to the energy of the machine. Any significant increase in the RMS value is an obvious indication of an emanating failure. Contrarily to what was expected, the change of RMS in this study was not significant, again to the light load that was applied to the tested bearing.

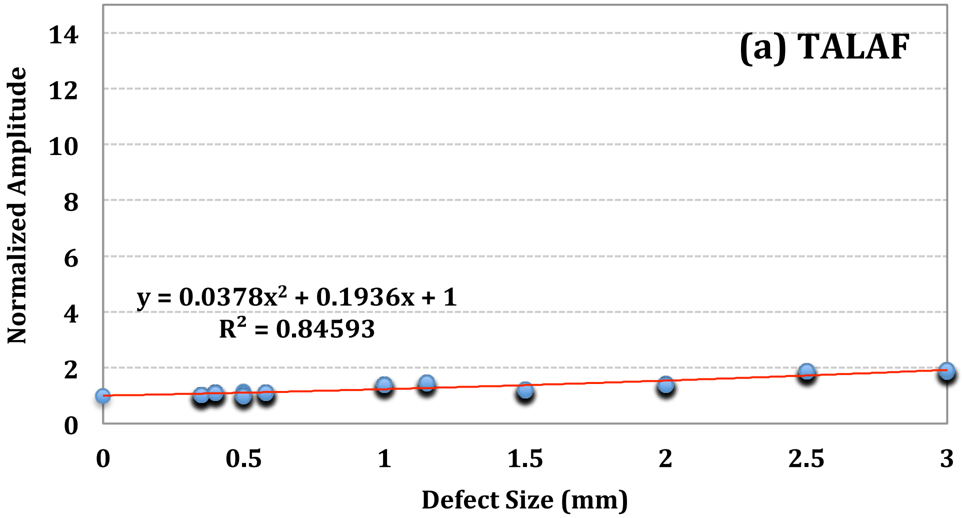
From the normalized figures of inner defects, it is clear that Kurtosis, Peak, Impulse Factor and Crest Factor are the most sensitive among all indicators. On the other hand, for the outer ring defects, Kurtosis, Peak, RMS and Impulse Factor are more sensitive than others. Therefore, only four parameters (Peak, RMS, Kurtosis and Impulse Factor) were used for further analysis and the rest of the parameters were excluded.

4.2.4 New Time Domain Parameters

All the parameters presented above showed an increase with defect size in different sensitivities rates. In general, kurtosis and peak were the most sensitive indicators toevolution of defects inside the bearing. Since the sensitivity of all parameters is variable through the time span of the bearing, one can think whether their combination by any mean, would generate a better parameter with higher sensitivity. In a previous paper [59], the introduction of TALAF and THIKAT was found to be more efficient in the health condition monitoring of damaged bearings. The same parameters will be tested again in this investigation, together with two more parameters introduced for the first time in this study; SIANA and INTHAR. The definitions of the four parameters are listed in Table 5 below.

Table 5: New time domain parameters

Indicator	Equation
TALAF	$\mathrm{TALAF} = \log\left(\mathrm{Ku} + \frac{\mathrm{RMS}}{RMS_0}\right)$
THIKAT	$\mathrm{THIKAT} = \log\left(Ku^{CF} + \left(\frac{\mathrm{RMS}}{RMS_0}\right)^{Peak}\right)$
SIANA	$\mathrm{SIANA} = \log\left(\frac{IF \times Peak^{CF}}{10^3 \times RMS^{Ku}}\right)$
INTHAR	$\mathrm{INTHAR} = \log\left(\frac{Peak^{Ku}}{RMS \times CF} + IF\right)$



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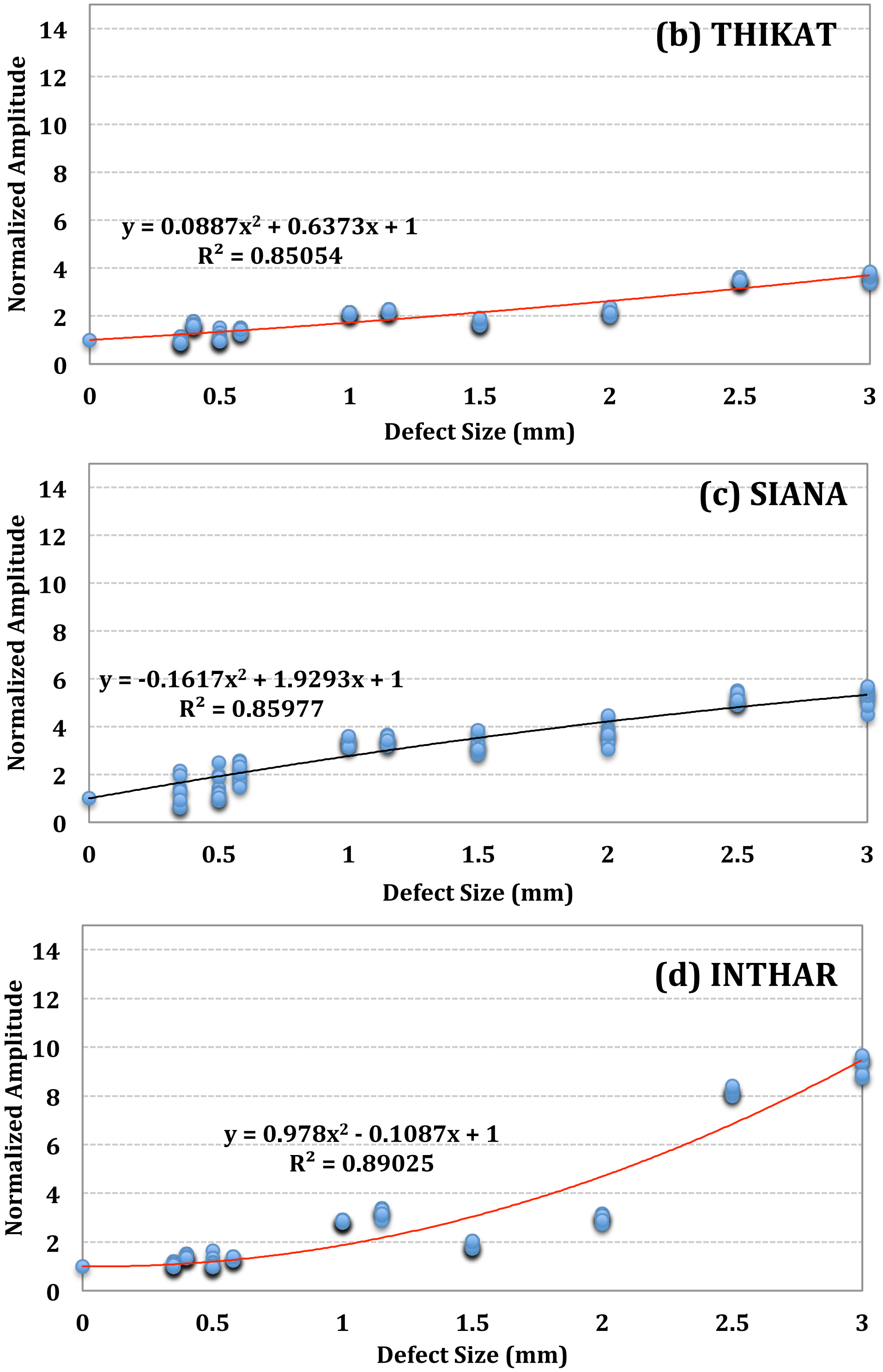
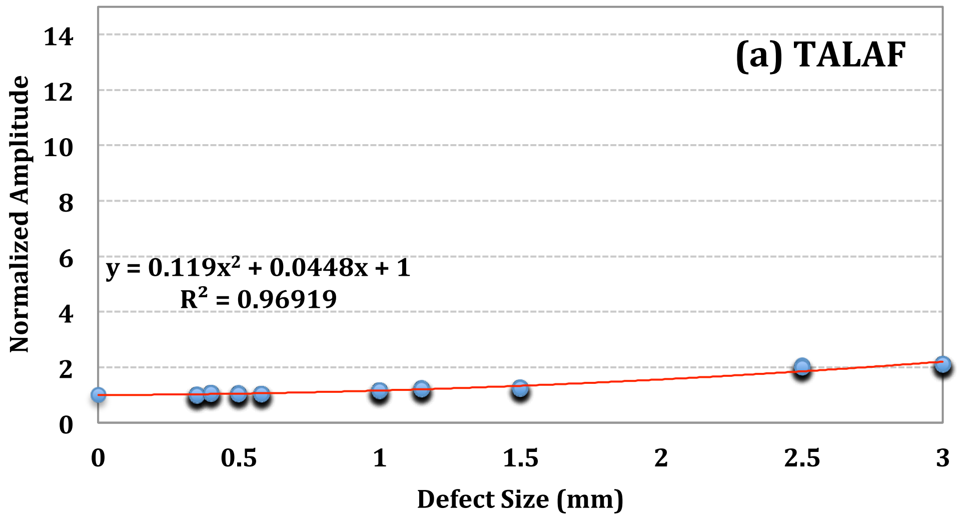
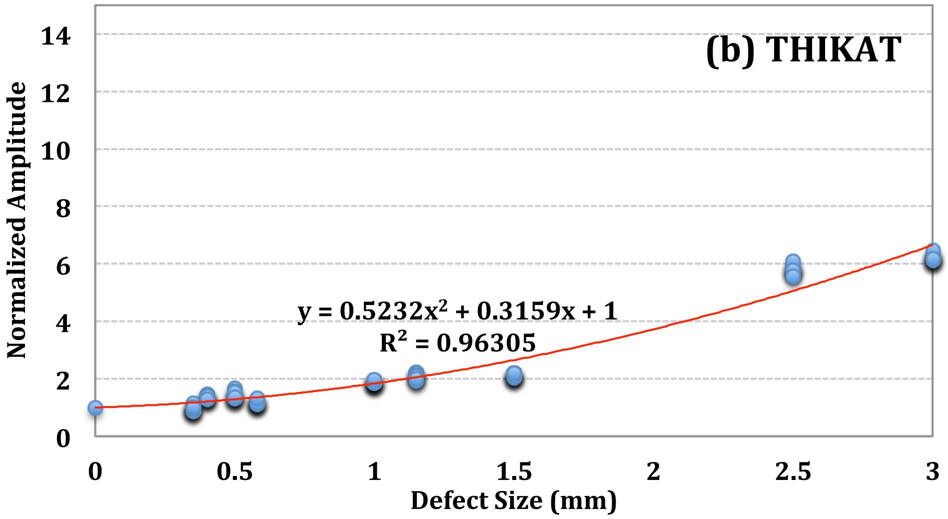
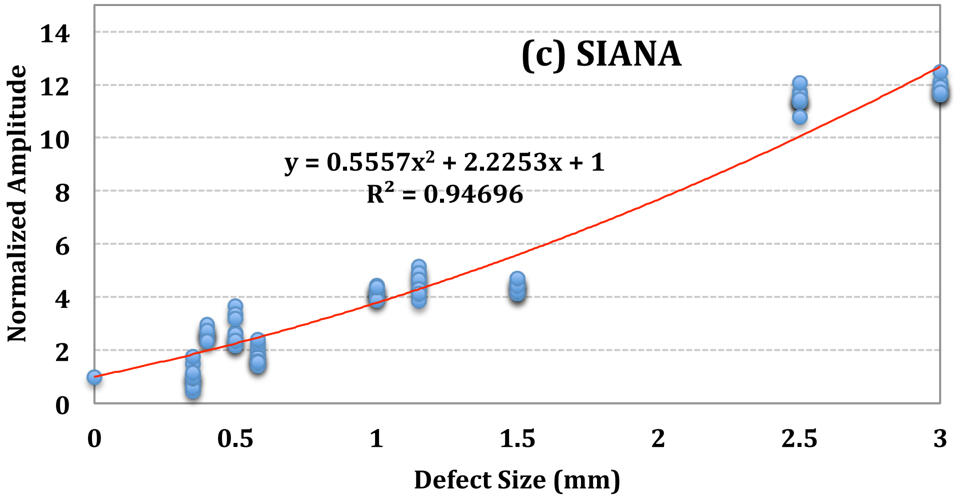


Figure 47: Normalized new time domain parameters for **outer** defects: (a) TALAF, (b) THIKAT, (c) SIANA, (d) INTHAR


(a) TALAF
y = 0.119x² + 0.0448x + 1
R² = 0.96919
Normalized Amplitude
0
2
4
6
8
10
12
14
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)


(b) THIKAT
y = 0.5232x² + 0.3159x + 1
R² = 0.96305
Normalized Amplitude
0
2
4
6
8
10
12
14
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)


(c) SIANA
y = 0.5557x² + 2.2253x + 1
R² = 0.94696
Normalized Amplitude
0
2
4
6
8
10
12
14
0
0.5
1
1.5
2
2.5
3
Defect Size (mm)

*continued

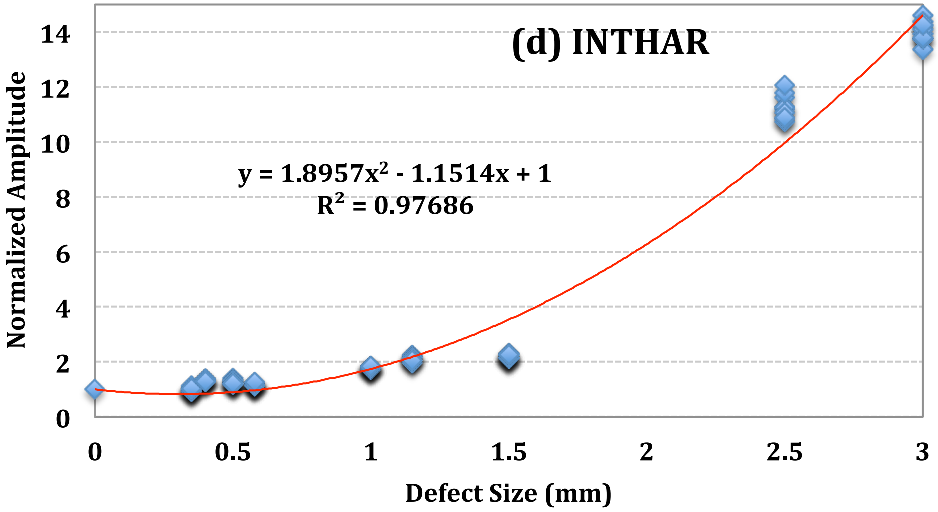


Figure 48: Normalized new time domain parameters for **inner** defects: (a) TALAF, (b) THIKAT, (c) SIANA, (d) INTHAR

The evolution of the new parameters is presented in Figure 47 and Figure 48 for outer and inner rings defects respectively. Table 6 below summarizes sensitivities of all time domain parameters in outer and inner cases. It is clear that SIANA and INTHAR have the best sensitivity among all other time domain indicators for both outer and inner cases. In addition, the response of THIKAT is almost similar to Kurtosis and TALAF is closer to RMS.

Table 6: Summary of all time domain parameters sensitivities (maximum values at maximum defect size)

Parameter	Peak	RMS	Kurtosis	IF	TALAF	THIKAT	SIANA	Inthar
Outer	3	2	**4**	2	2	4	**6**	**10**
Inner	3	1.5	**5.5**	3	2	6	**12.5**	**15**

4. 3 Frequency Domain Analysis

The frequency domain analysis consists of two main investigations. One is locating the harmonics of the fault frequencies (BPFO or BPFI) on the spectrum and then measuring the amplitudes of each one of them and the other is localizing sidebands of BPFO and BPFI. Both analyses will be investigated in this chapter. Table 7 below shows the expected values of BPFO and BPFI for the particular rotational speed of 18.26 Hz. In general, the number of harmonics increases with the severity of defect and the harmonics that are more sensitive to the defect depend of the mechanical system. In this study, only the three first harmonics were considered.

Table 7: BPFO and BPFI and their multiples

	Calculated	x1	x2	x3
BPFO	3.577 Hz	65.3 Hz	130.6 Hz	195.9 Hz
BPFI	5.422 Hz	99.0 Hz	198.0 Hz	297.0 Hz

The peaks of the three first harmonics of BPFO and two first harmonics of BPFI, are displayed in Figure 49.

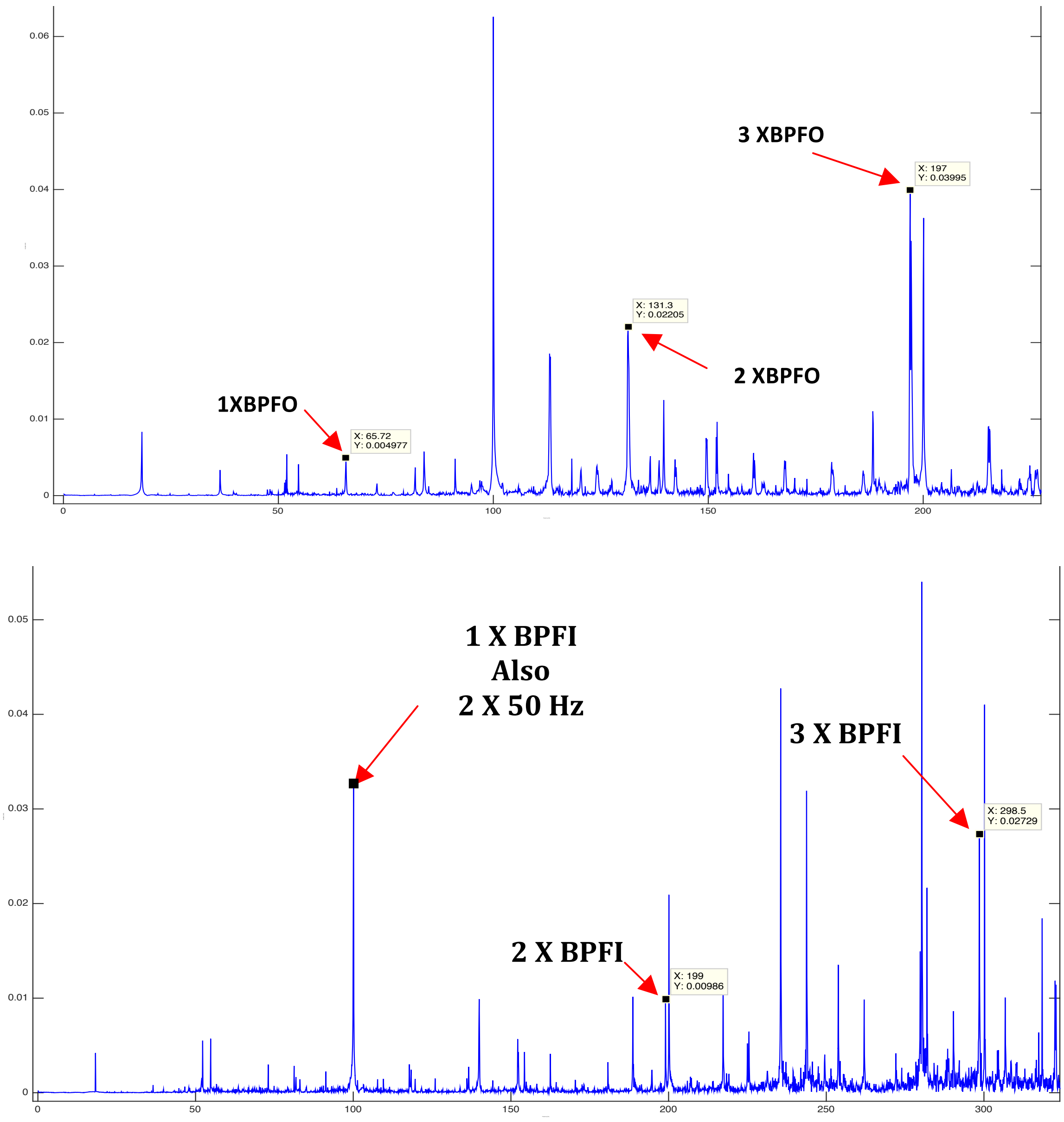
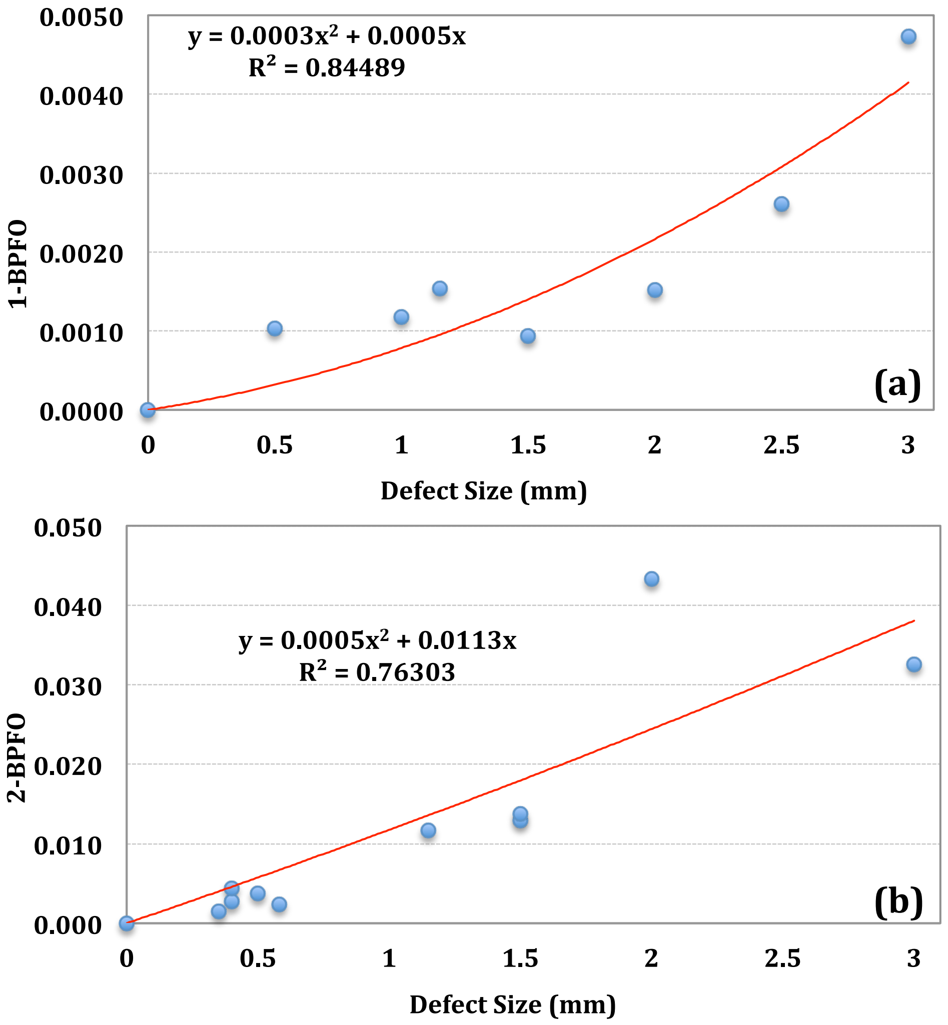


Figure 49: Peaks of first three harmonics of BPFO and first two harmonics of BPFI

When the defects were located on the outer ring, all three harmonics of BPFO were visible on the spectrum; Figure 50 shows the evolution on BPFO and its harmonics with increasing defect size. However, when the defects were located on the inner ring, only second and third multiples of BPFI were visible as displayed Figure 51.



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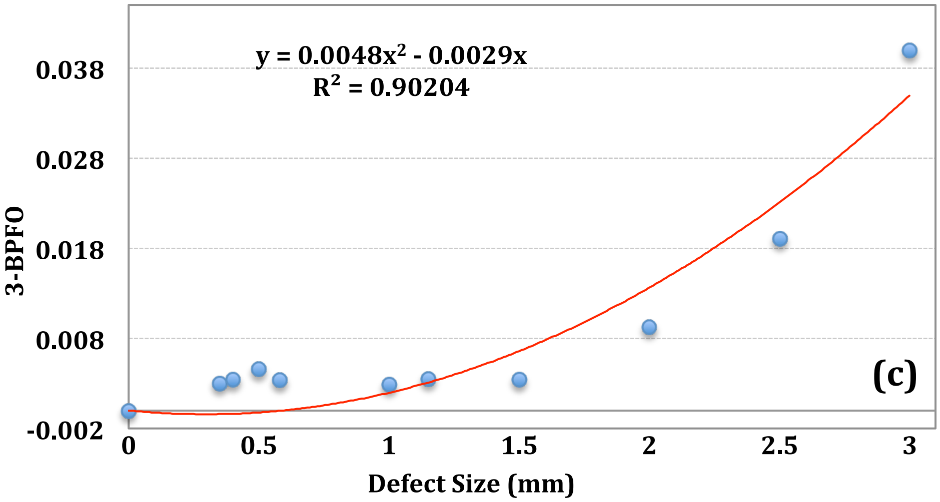
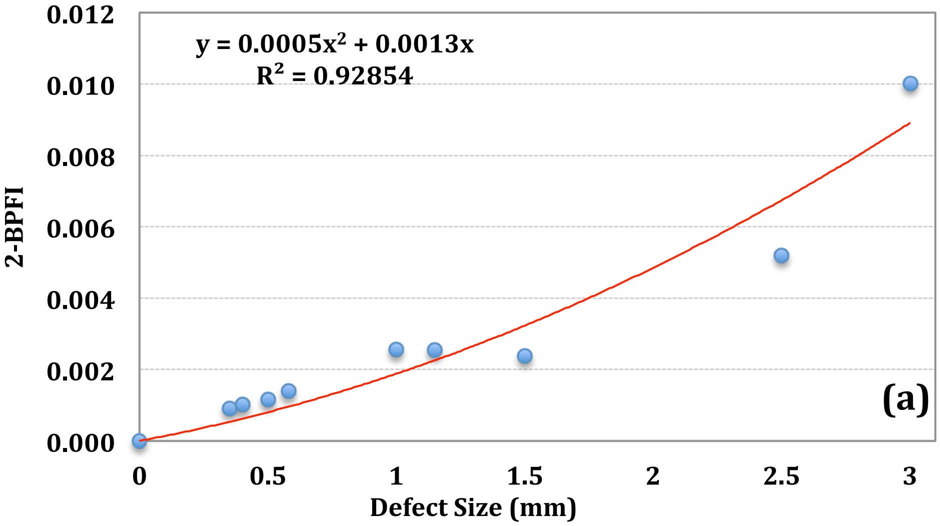


Figure 50: Harmonics of BPFO: (a) 1xBPFO, (b) 2xBPFO, (3) 3xPBFO



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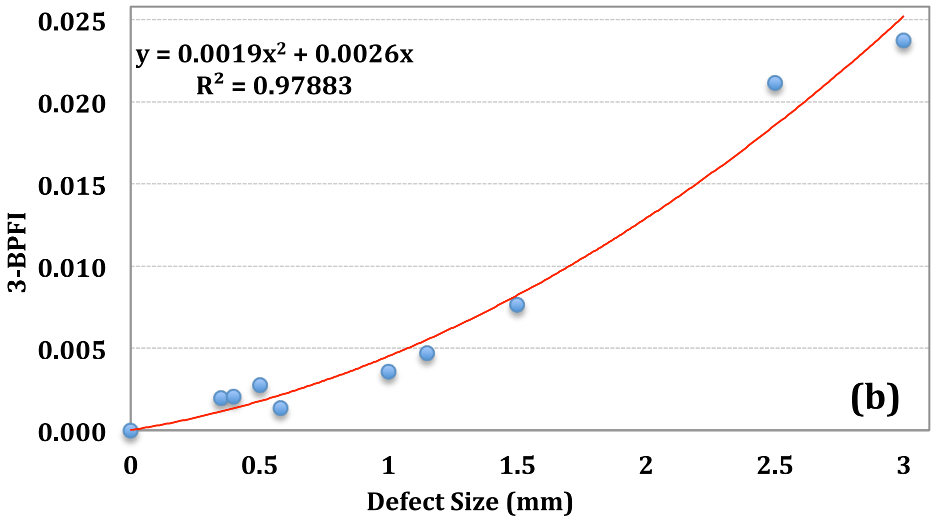


Figure 51: Harmonics of BPFI: (a) 2xBPFI, (b) 3xBPFI

For both BPFO and BPFI and their harmonics, one can see the presence of an obvious increase of their amplitudes with growing defect diameter. As done for the time domain analysis, both inner and outer vibrational responses in frequency domain were compared Figure 52. It is clear that the response of the outer ring defected bearing is slightly higher than the inner.

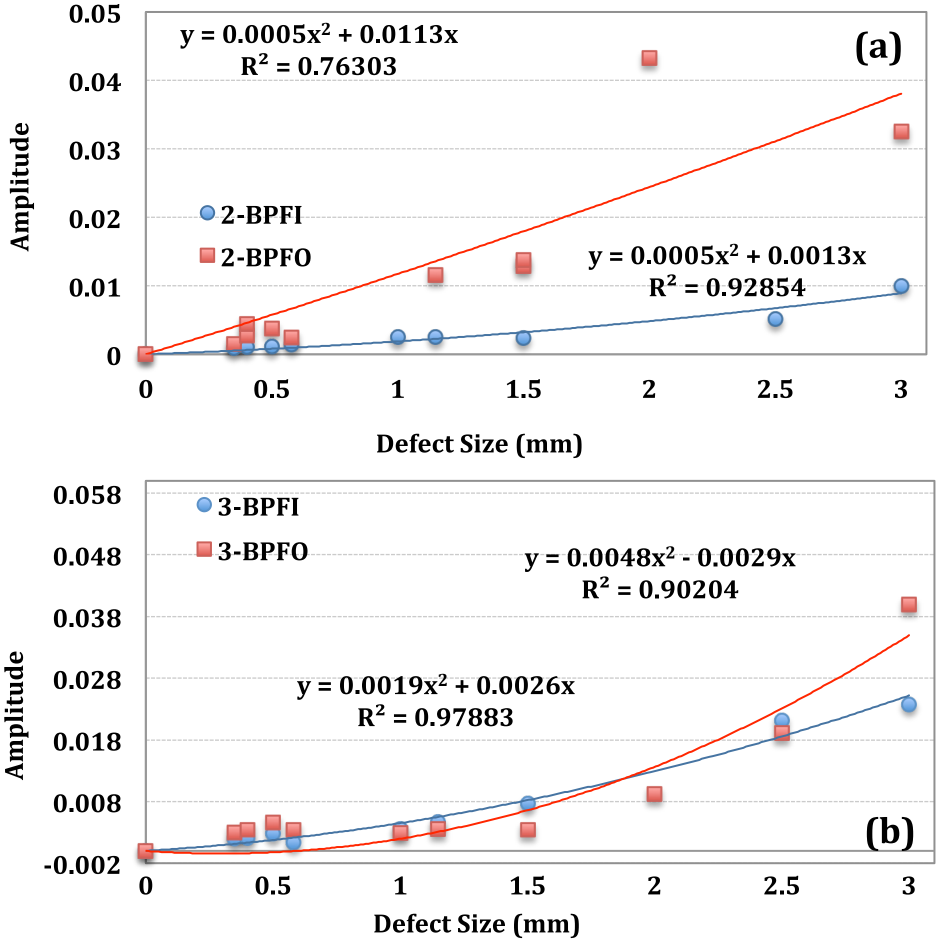
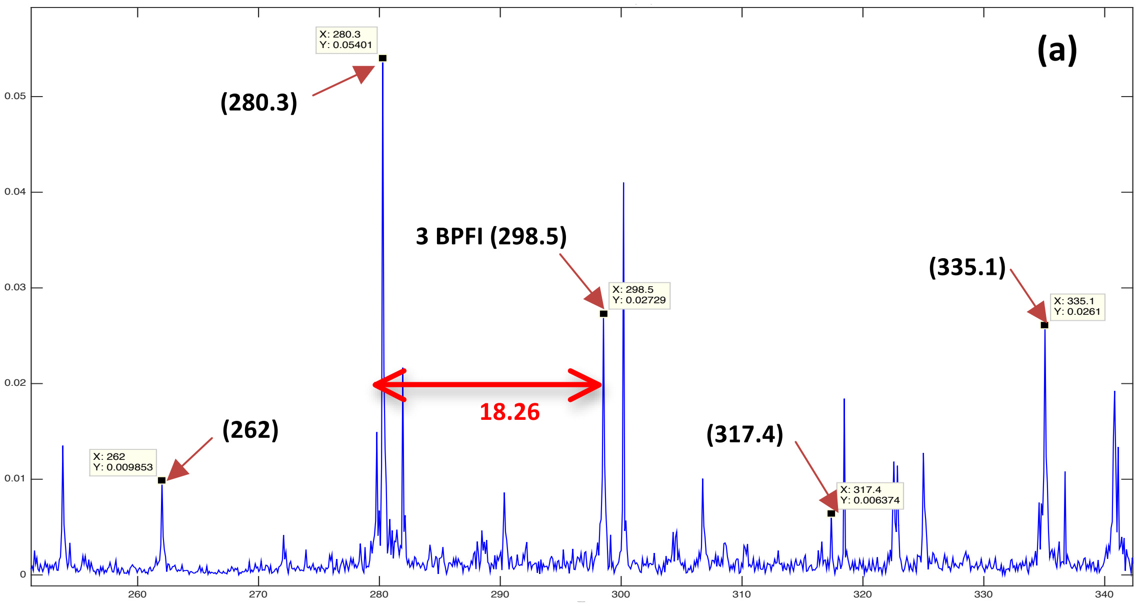


Figure 52: Comparison between inner and outer vibrational responses in frequency domain: (a) 2xBPFI and 2xBPFO, (b) 3xBPFI and 3xBPFO

Another method to identify bearing defects in frequency domain is the sidebands detection. For both cases, inner and outer ring faults clear sidebands were located around bearing fault frequency and the difference between sidebands was 18.26, which represents the rotational speed as displayed in Figure 53. In general, sidebands were noticeable for big defect size, while it was not visible in case of smaller defects. In addition the number of sidebands increases along with progression in defect sized as shown in Figure 54. One can see that the sidebands effect in the spectrum was stronger in case of inner ring defects. This result matches with previous findings of Tandon Nakra [80]. This is probably due to the fact that, when the defect is located on the inner ring and that ring is rotating, there is entrance into the load zone once every cycle, and the passing through the load zone occurs at the rotational speed. Therefore the sidebands with 18.26 Hz around BPFI were more obvious.



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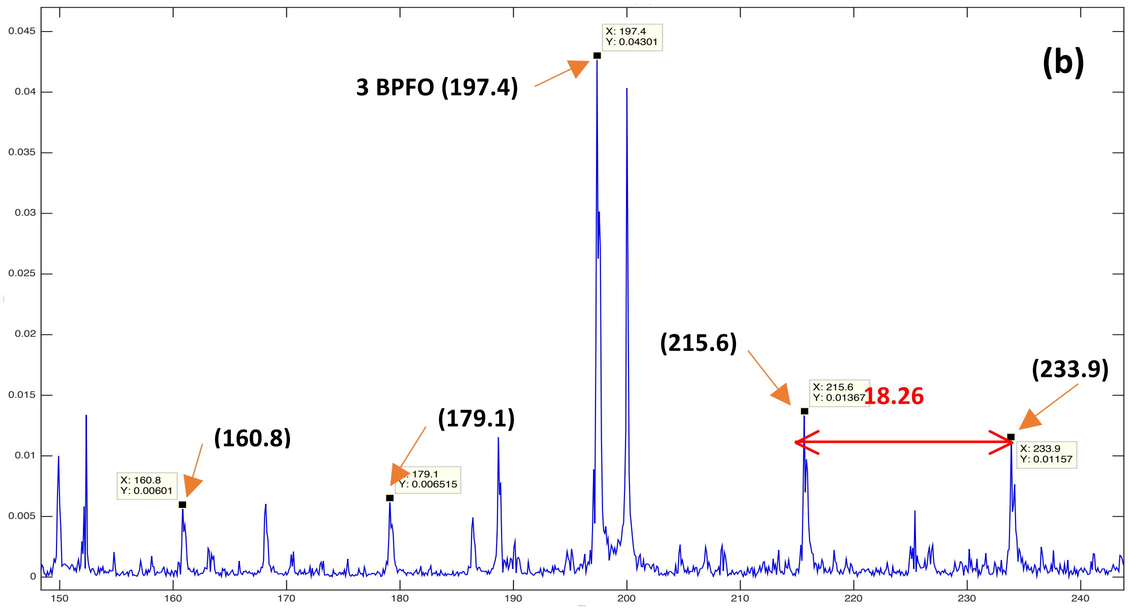
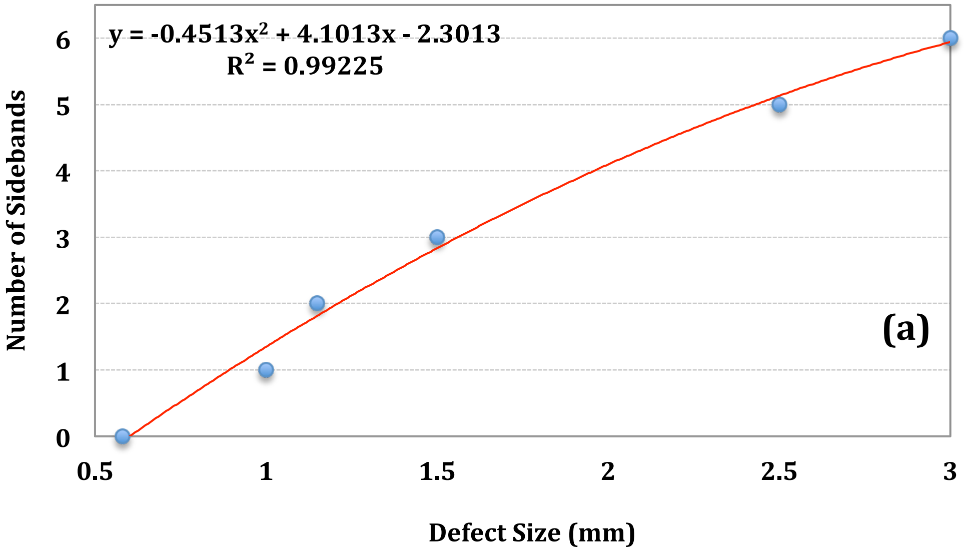


Figure 53: First two sidebands: (a) 3 BPFI and sidebands, (b) 3 BPFO and sidebands



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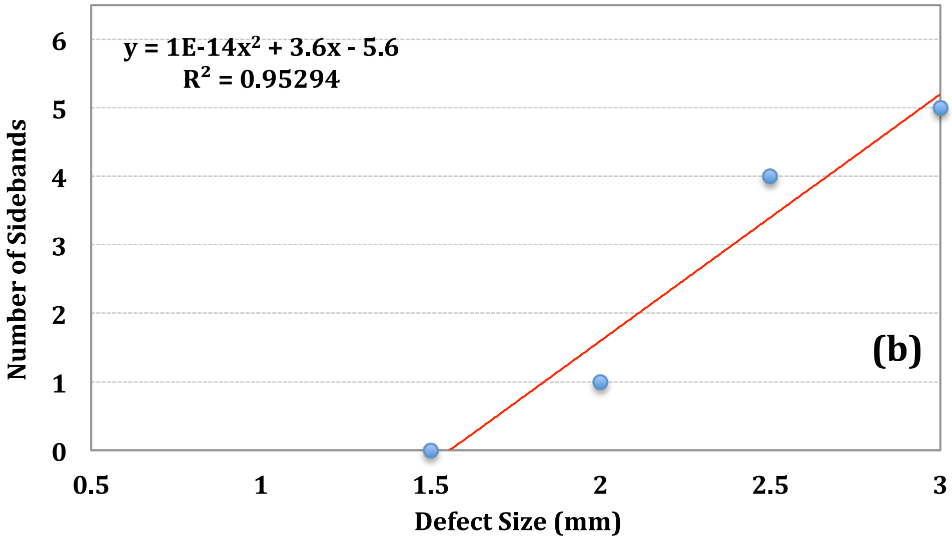


Figure 54: Number of sidebands with defect size: (a) Inner ring defects, (b) Outer ring defects

4.4 Time and Frequency Comparison

At the end of this section, it is essential to come up with a comparison between time domain analysis and frequency-domain analysis. As mentioned previously, all the proposed parameters in the frequency domain were starting from zero. However, all the time-domain parameters were normalized to start from one. To make the comparison possible between both families of parameters, we have to consider an intermediate state of degradation as the origin and make all the comparisons relatively to this state. Therefore, the defect size 0f 0.50 mm was considered as a common reference. This will allow for tracing the amount of increment and the sensitivity of all parameters in different domains. The sensitivity summaries after normalization to 0.5 of both time and frequency domain parameters are displayed in Figure 55, Figure 56 and Figure 57.

All the time-domain and frequency-domain scales are now unified, and a direct comparison between all parameters would be possible. In general, one can see that parameters extracted from frequency-domain appear as more sensitive than traditional time domain indicators to defect size growth. This result is perhaps because the time domain signal is accounted for the contributions of all vibration responses generated by all components of the machine and each parameter is representative to one side of the signal. On the other hand, the information collected from the frequency domain represents the contribution of one single element, which is the bearing in this case. By combining different conventional time domain parameters in new indicators, i.e., TALAF, THIKAT, SIANA and INTHAR, the sensitivity improved significantly and became even competitive with BPFO and BPFI. Table 8 shows all sensitivities of all time and frequency parameters.

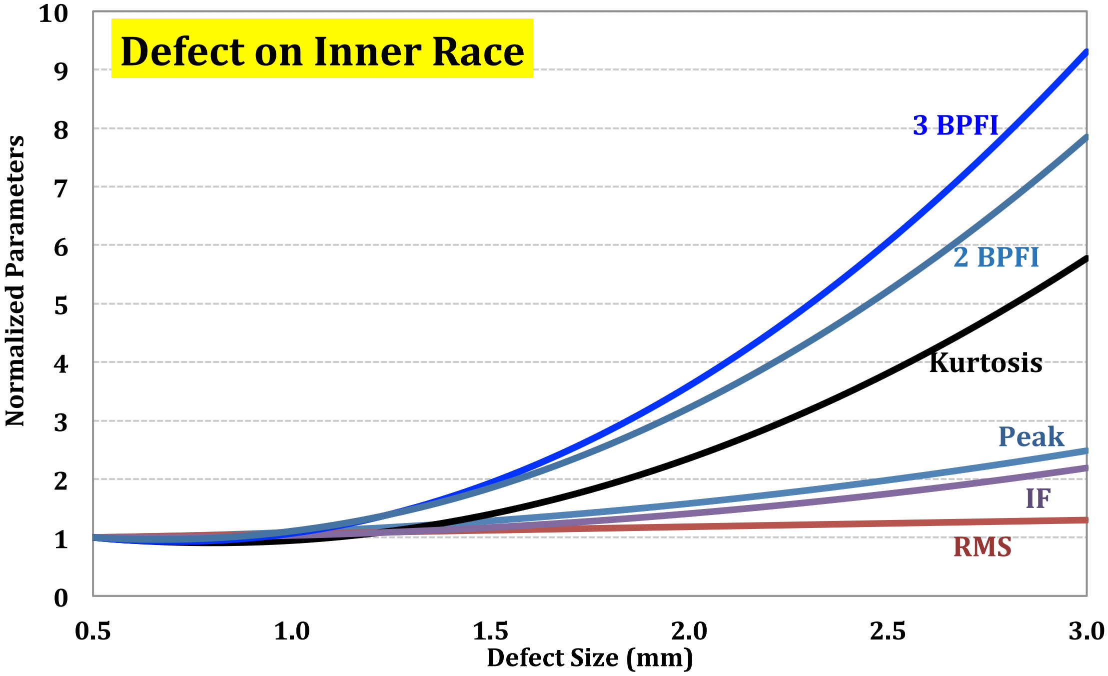


Figure 55: Time domain and frequency domain parameters for **inner** ring defects

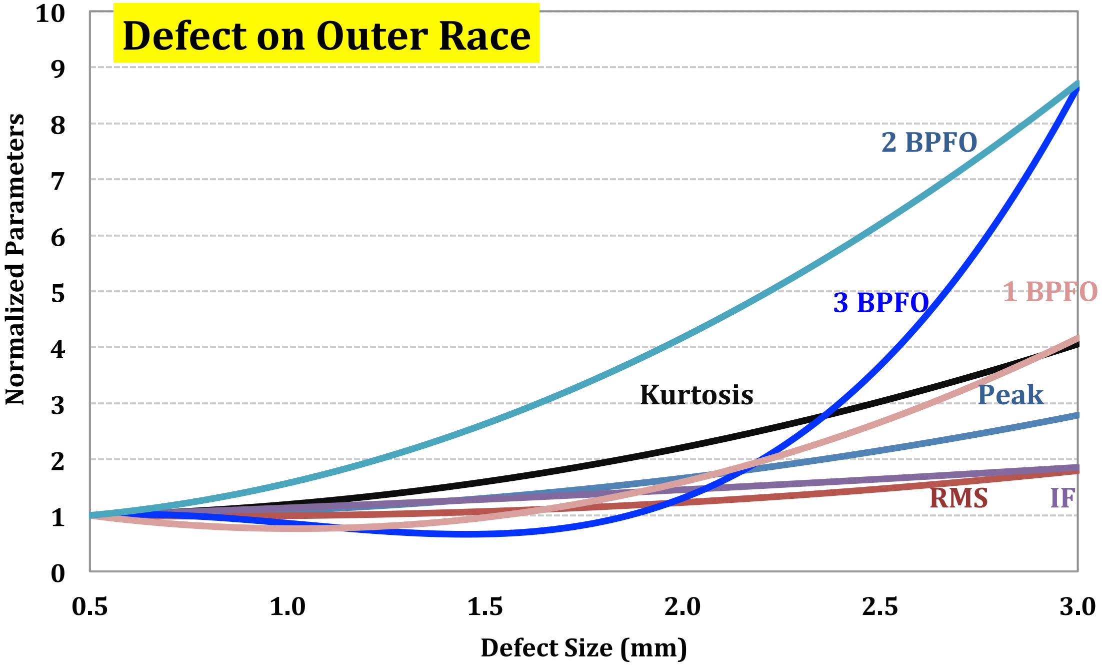
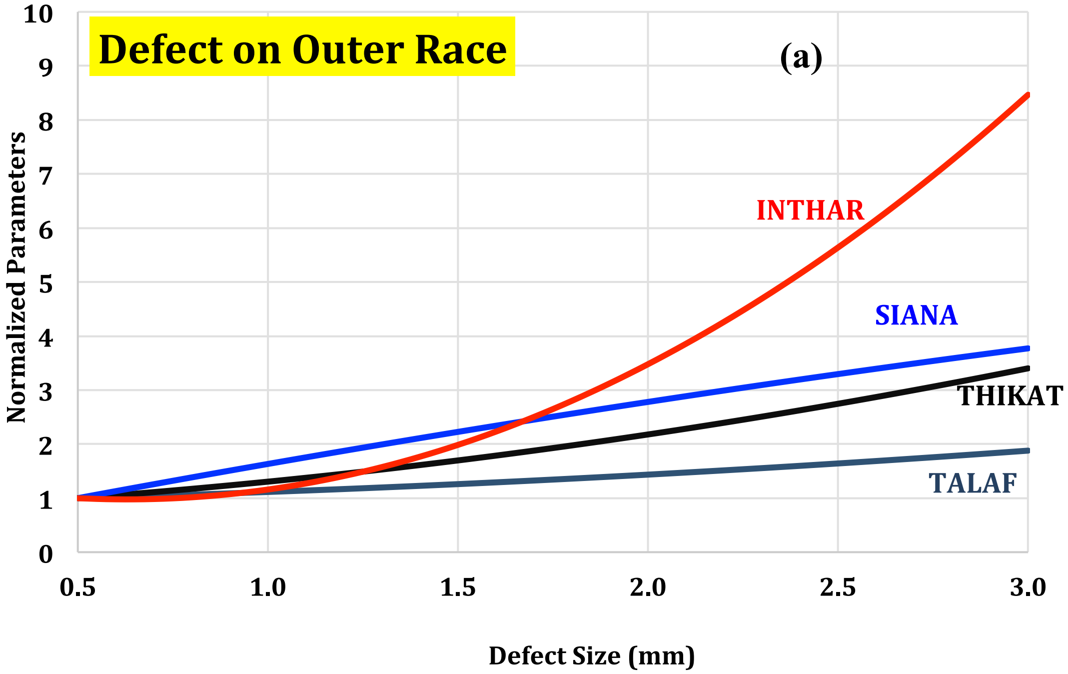


Figure 56: Time domain and frequency domain parameters for **outer** ring defects



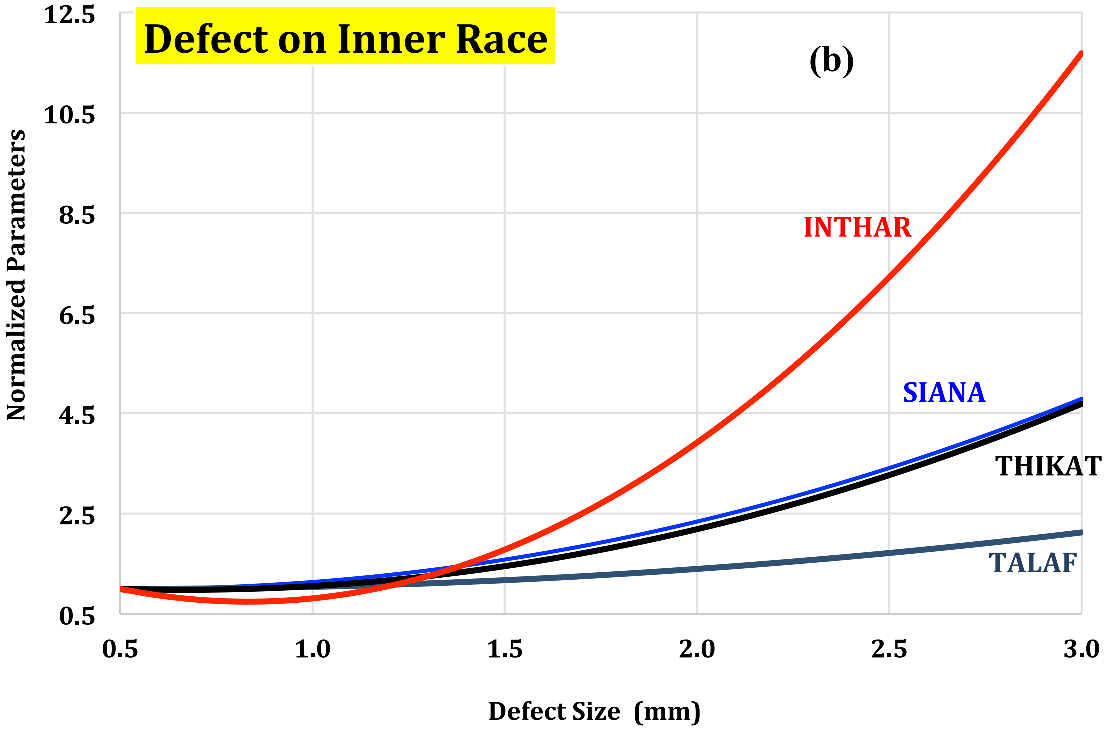


Figure 57: Normalized new time domain parameters: (a) Outer ring defects, (b) Inner ring defects

As a summarized in Table 8, the sensitivity comparison between all parameters extracted from time-domain and frequency-domain reveal that INTHAR, SIANA, THIKAT and Kurtosis are the best time-domain parameters for health condition monitoring of bearings. Otherwise, second and third harmonics of BPFO and BPFI are the most sensitive meters to bearing health degradation, in the frequency-domain.

Table 8: Sensitivity of time and frequency domain indicators normalized to 0.5

Parameter	**Inner**	**Outer**
Peak	2.5	3
RMS	1.5	2
Kurtosis	**5.5**	**4**
Impulse Factor	2.1	2
TALAF	1.8	2.2
THIKAT	3.5	4.7
SIANA	3.7	4.7
INTHAR	**8.5**	**11.7**
1 X Fault Frequency	-	4.5
2 X Fault Frequency	**8.6**	**8.6**
3 X Fault Frequency	**8.5**	**8.5**

In summary, the direct FFT and time domain parameters reveal the defect at the third level of degradation where the defect is already big enough to affect the performance of the machine and disturb its operation. For example, in Figure 55 detection begins at 1 mm. In next section, the method of Envelop Detection (ED) will be investigated in order to explore its suitability for health condition monitoring of damaged bearings and see how it can be used to detect the defects at earlier stage than direct spectrum and time domain.

4.2 Envelope Analysis

4.2.1 Introduction

Envelope Detection (ED), also sometimes referred to as High-Frequency Resonance Technique (HFRT) or amplitude demodulation, is a well-known signal processing technique. This technique intends to extract bearing defects characteristic frequencies that may not be clear at low-frequency spectrum because of the disturbing contribution of vibrations arising from other machine components and/or noise. The primary goal of enveloping analysis is to detect faults in rolling element bearings and gearboxes at an early stage. Skipping of the early fault detection technique as the one above leads to the detection of the failures at later stages when defects appear already advanced. This significantly shortens the remaining life of machine elements that may appear to be failing with more advanced damage by this time, which could be prevented by earlier detection of faults.

The idea behind the ED is based on demodulation of bearing element impacts from high-frequency resonance. In rolling element bearings, each time a rolling element strikes the defect on inner or outer races, an impact is generated. These impulses represent bearing fault frequencies such as BPFO, BPFI and BSF [83, 88]. Since the duration of these impulses is extremely short, their energy will be distributed over a wide range of frequencies. Consequently, a multitude of peaks will be generated but at very low level. This fact complicates the detection of bearing defects by direct spectrum analysis.

However, the generated impacts usually excite the natural frequencies of the system [88]. Therefore, high amplitudes resonances (usually located at high frequencies) are encountered on the response spectrum. What happens physically around such resonance frequencies is an amplification of the energy level within a narrow band of frequency[84]. The main idea of the ED technique is to take advantage of such amplification phenomenon.

Envelope detection as a process involves several steps, which aimed at the extraction of desired signal trends from overall vibration spectrum Figure 58.

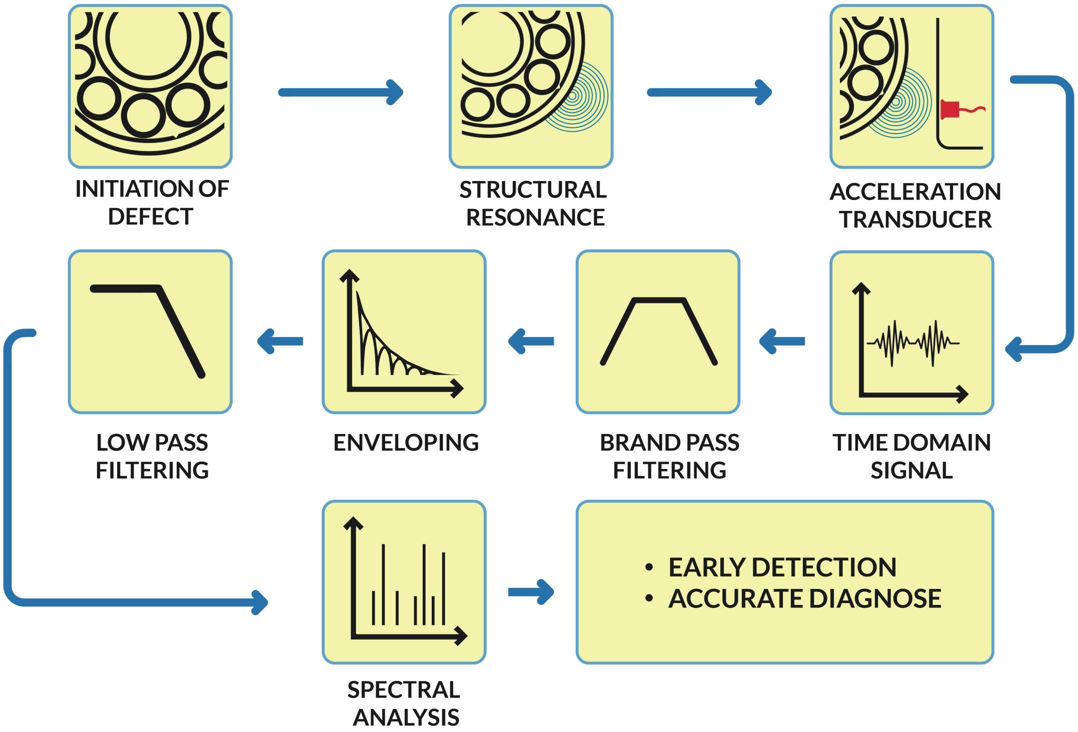


Figure 58: Typical steps in the implementation of enveloping [85]

In practice, analysis of the enveloping process begins by applying the bandpass filter around one of the natural frequencies in order to eliminate undesired vibration signals from other sources at low frequency and enhance signal to noise ratio [88]. The structural resonance of the bearing is selected as a central (leading) frequency in the bandpass filter. The resonance frequency is usually identified by application of the impact tests on the system for this particular point. Moreover, spectral kurtosis and Kurtogram can be used as approximate estimation of the optimal center frequency and bandwidth for resonance demodulation with envelope analysis [48, 88]. However, performing of the impact tests is not mandatory, since the resonant frequency can be clearly visualized in the raw signal spectrum as well [84]. At the next step, an envelope is applied to the band passed signal. There are different strategies for envelope extraction in general, which are commonly applied in practice; Hilbert Transform method was used in this study for the envelope extraction.

The envelope signal is smoothened by low pass filter afterward, to remove the carrier signal, i.e., irrelevant bandpass filtered resonance frequency. Finally, the spectrum of the signal is generated to visualize bearing defects characteristic frequencies.

4.2.2 Envelope Detection by Hilbert Transform

This method works by creating the analytic signal of the input by using a Hilbert transformer. An analytic signal is a complex signal, where the real part is the original signal and the imaginary part is the Hilbert transform of the original signal. In early 20th century, the German scientist David Hilbert (1862-1943) demonstrated that the function ***sin (ωt)*** equals to the Hilbert transform of ***cos (ωt)***. This finding yielded the ±π/2 phase-shift operator, which is the core feature of Hilbert transform. Real function f(t) and its Hilbert transform f^(t) correlate with each other in a way to create the mutual strong analytic signal. However, the fact that a function and its Hilbert transform possess the similar energy, gives us the chance to apply this energy for quantitative assessment of calculation accuracy for approximated Hilbert transform [86].

The Hilbert transform of a function f(x) is defined by the following equation:

$$F(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{f(x)}{t-x}\, dx$$ **Equation 6**

The Hilbert transform actually works as a filter, shifting the phases of all frequency components of its input by -π/2 radians.

We can build the "analytic" (complex time) signal Y(t) from a real-valued input signal y(t) by equation bellow:

$$Y(t) = y(t) + j\, h(t)$$ **Equation 7**

Where,

- Y(t) is the analytic signal (built by combination of input signal and its Hilbert transform)
- y(t) is the input signal itself
- h(t) represents the Hilbert Transform of the input signal [87].

For instance, if we use the Hilbert transform **H** to calculate a new time signal **h(t)** from the original time signal **y(t) (**which is a sing function), we will get the time signal **h(t)** as a cosine function, both are shown in Figure 59.

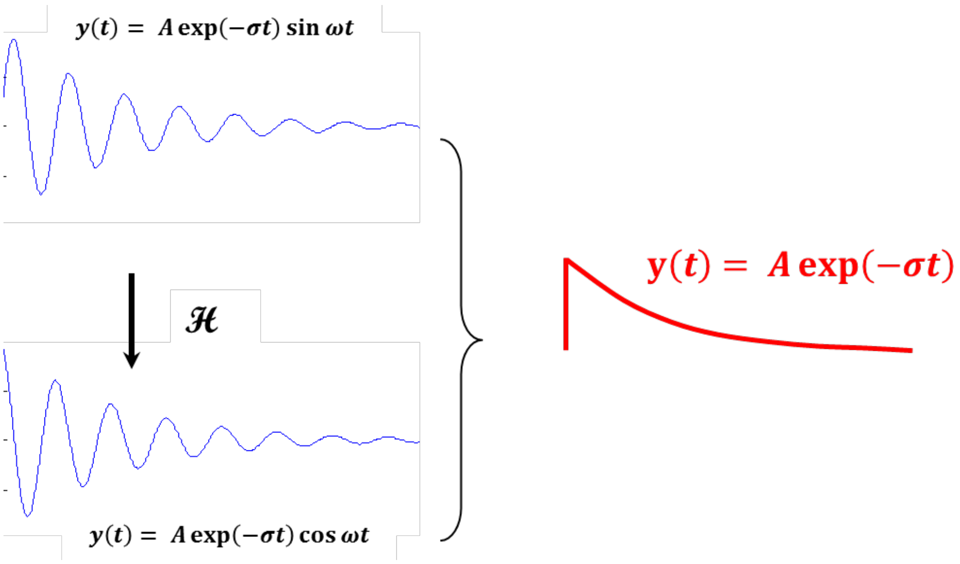


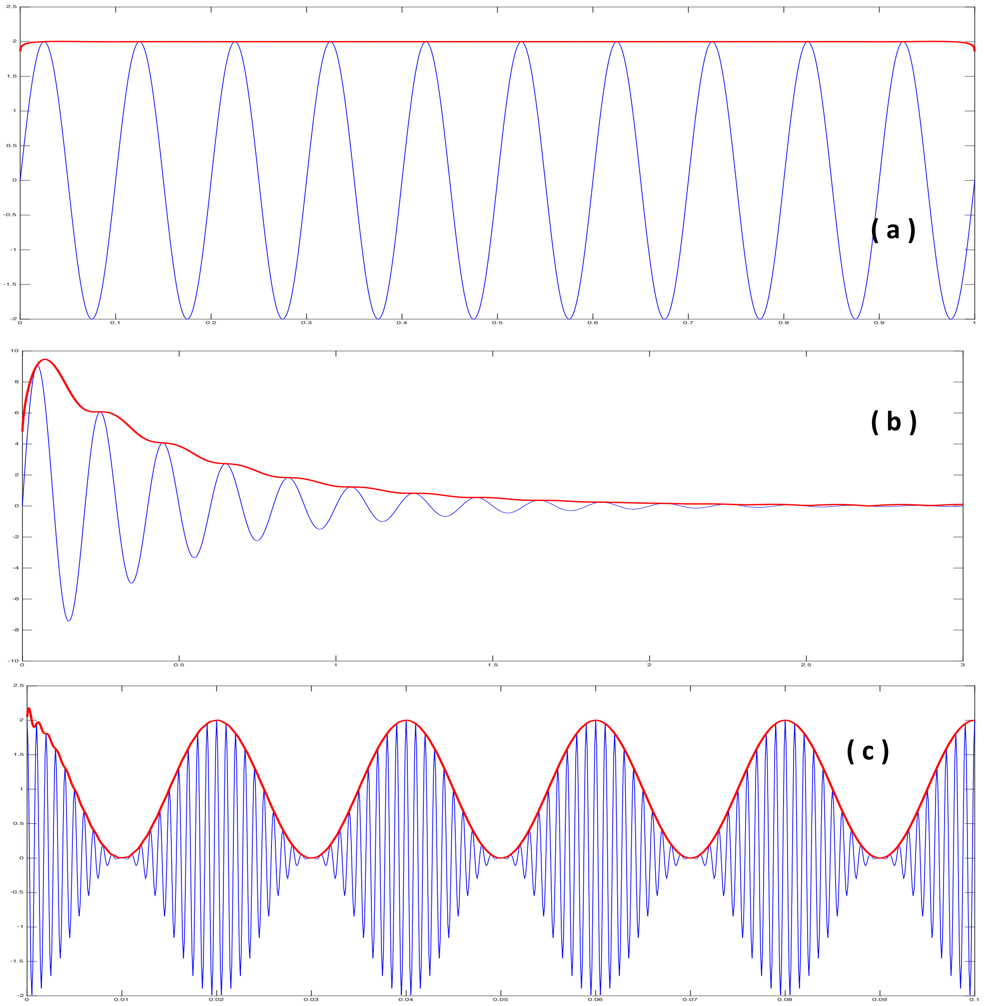
Figure 59: Envelope detection of an exponentially decaying signal, by Hilbert transform

4.2.3 Application of Hilbert Transform on Some Particular Waves

Before using the Hilbert Transform as a fundamental tool to obtain the envelope of a real signal generated by the tested bearing, the efficacy of such operator on some particular waves was tested on simple signals:

- case 1: $y(t) = 2\times\sin(2\pi\times 10\times t)$
- case 2: $y(t) = 10\times\sin(10\pi\times t)\times\exp(-2t)$
- case 3: $y(t) = 1 + \cos(2\pi\times 50\times t)\times\cos(2\pi\times 1000\times t)$

The simulation results relative to the three signals mentioned previously are plotted in Figure 60. One can see how effective this operator to depict the envelope of the original wave is. The curve in red related to the Hilbert transform appears obviously as an envelope of the original time curve in blue. The application of the Hilbert Transform on a real signal measured from defected bearing is showed in Figure 60-d.



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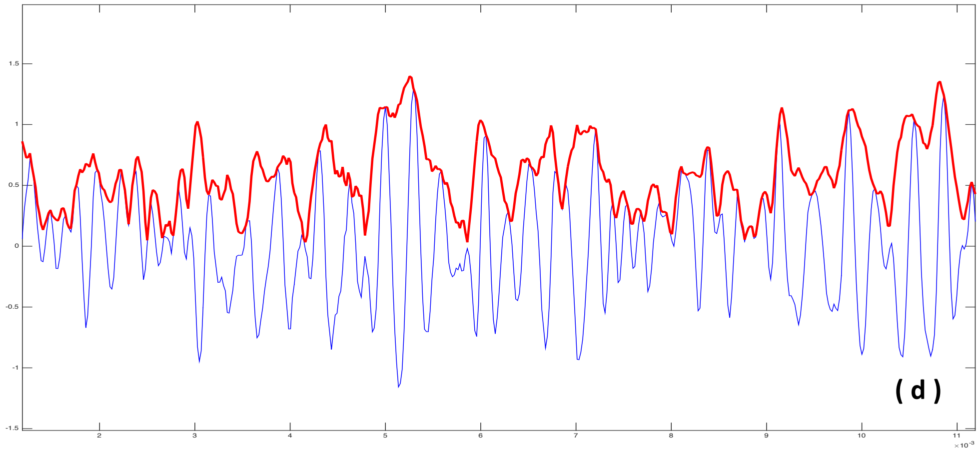


Figure 60: Envelope detection by Hilbert transformation: (a) sine signal, (b) Decaying signal, (c) Modulated signal, (d) Real bearing signal

4.2.4 Results of Envelope Analysis

In conclusion of this part, it was clear that the envelope detection by Hilbert transform was an effective way to detect the envelope of all kind of signals. This method was applied on all inner and outer rings defected bearings to extract the bearing fault frequencies. Figure 61 shows the difference between normal spectrum and envelope spectrum, while Figure 62 and Figure 63 represents the evolution of amplitude of bearing characteristics frequencies with defect size for outer and inner defects, respectively.

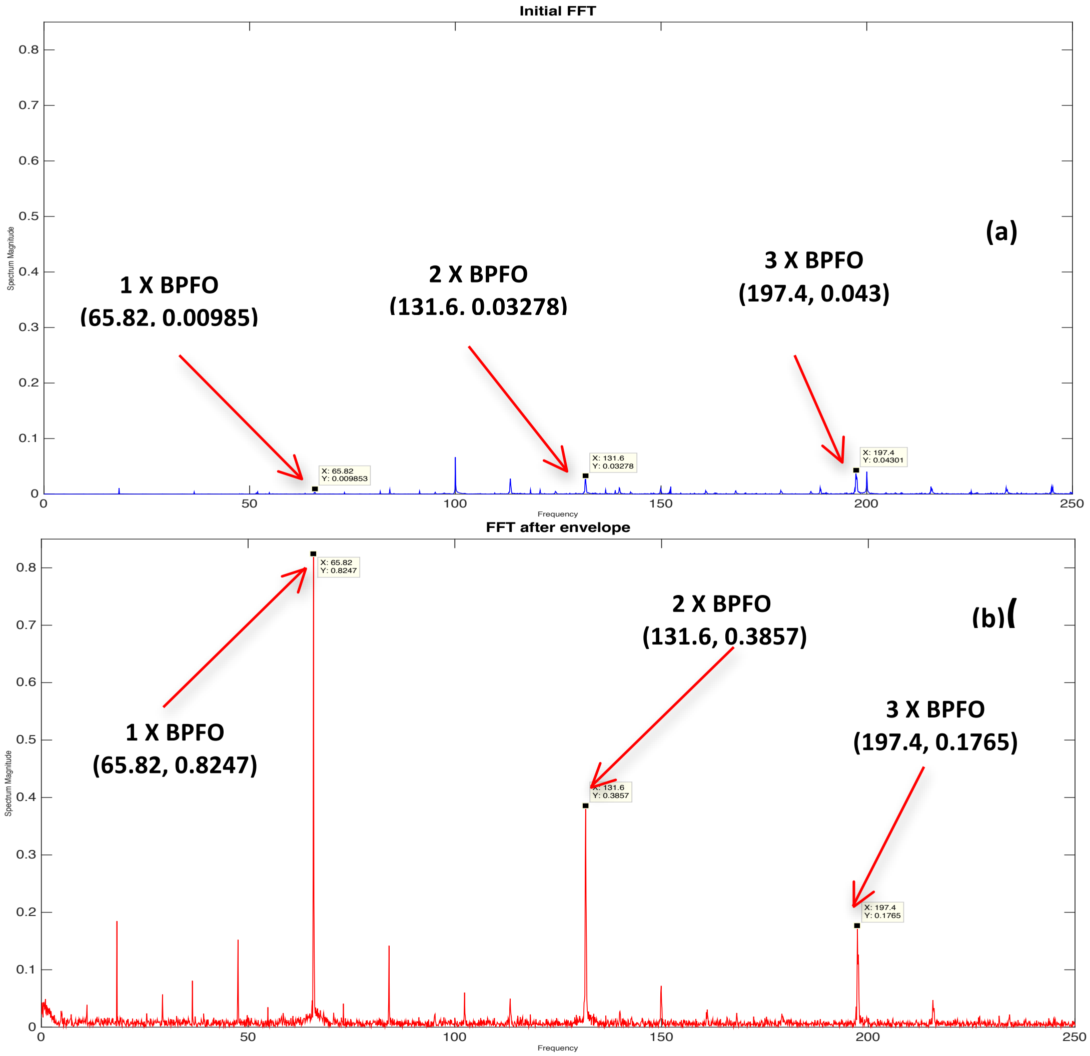


Figure 61: Bearing Fault Frequencies: (a) Direct spectrum, (b) Enveloped spectrum

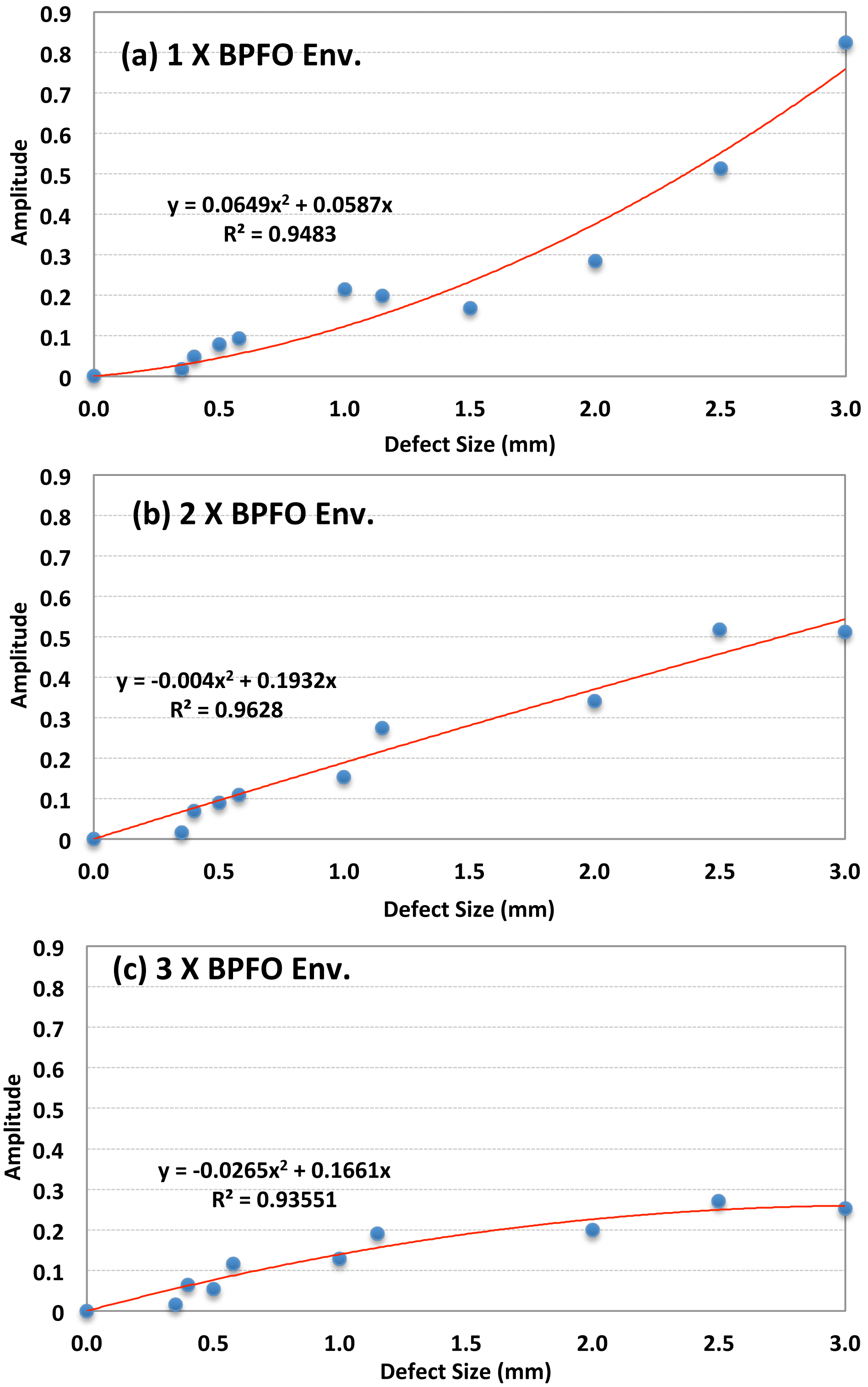


Figure 62: Harmonics of enveloped BPFO: (a) 1xBPFO, (b) 2xBPFO, (3) 3xPBFO

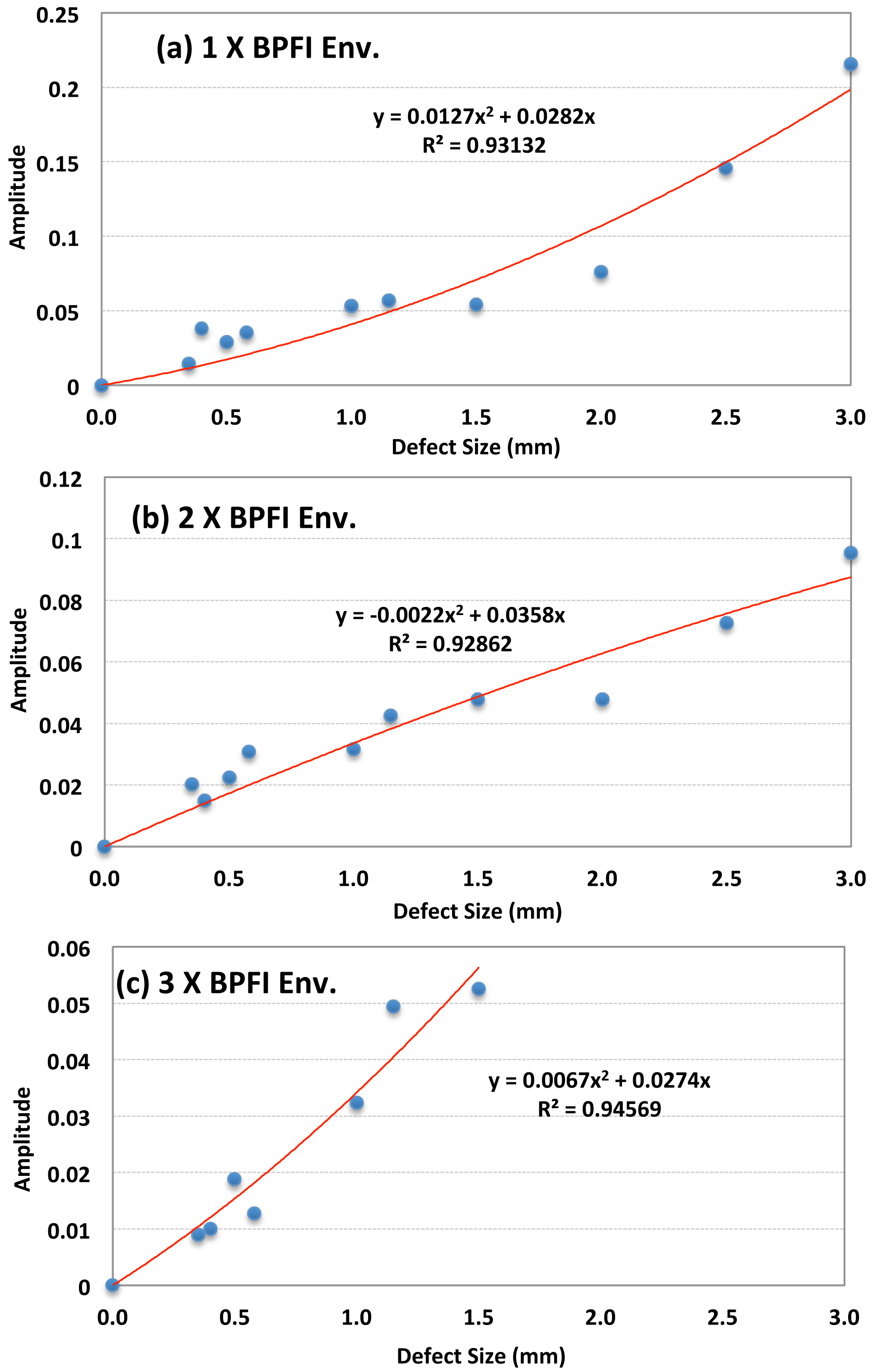
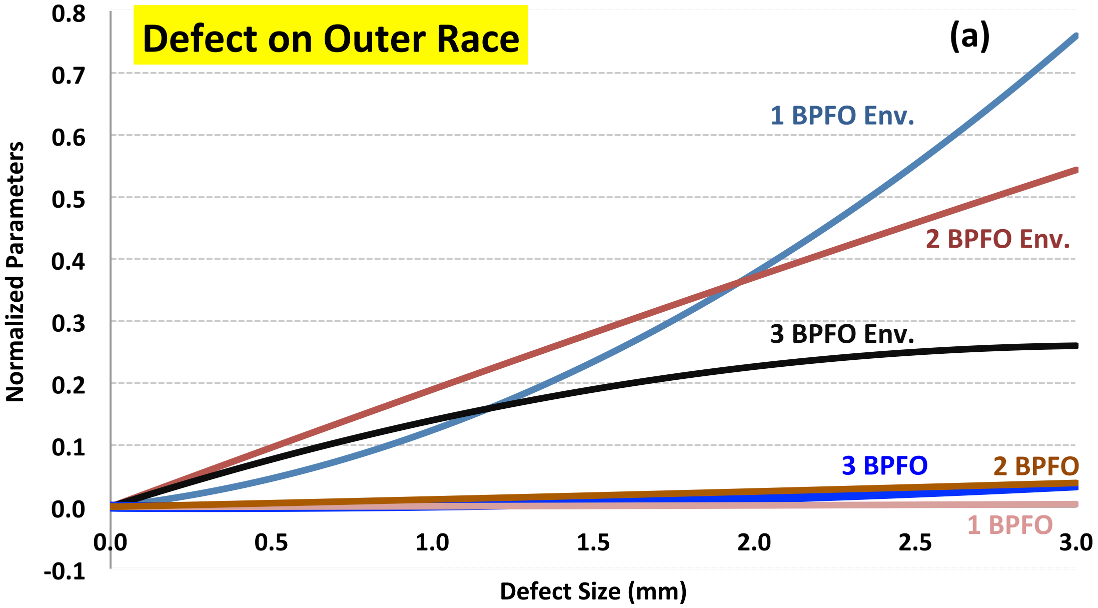


Figure 63: Harmonics of enveloped BPFI: (a) 1xBPFI, (b) 2xBPFI, (3) 3xPBFI

At the end of this section, it’s necessary to come up with a comparison between frequency domain analysis with and without envelope technique. All harmonics of BPFO and BPFI are plotted in Figure 64 a and b respectively. Its clear that the bearing fault frequencies can be extracted from the spectrum easier after using envelope technique. Comparing direct spectrum with enveloped one; the amplitude of fault frequency was improved by more than 70 percent which allows for detection of defects at its early stage (stage two of degradation). Moreover, the response of outer ring defects was clear in comparison with inner ring defects. In addition, the envelope technique helps in removing the peaks of 50 Hz and its multiples (electrical related frequencies). In case of inner ring defects, the BPFI and its multiples were very close to these electrical peaks and was not visible clearly in the direct spectrum, while it was noticeable in the enveloped signal after the electrical peaks were filtered.



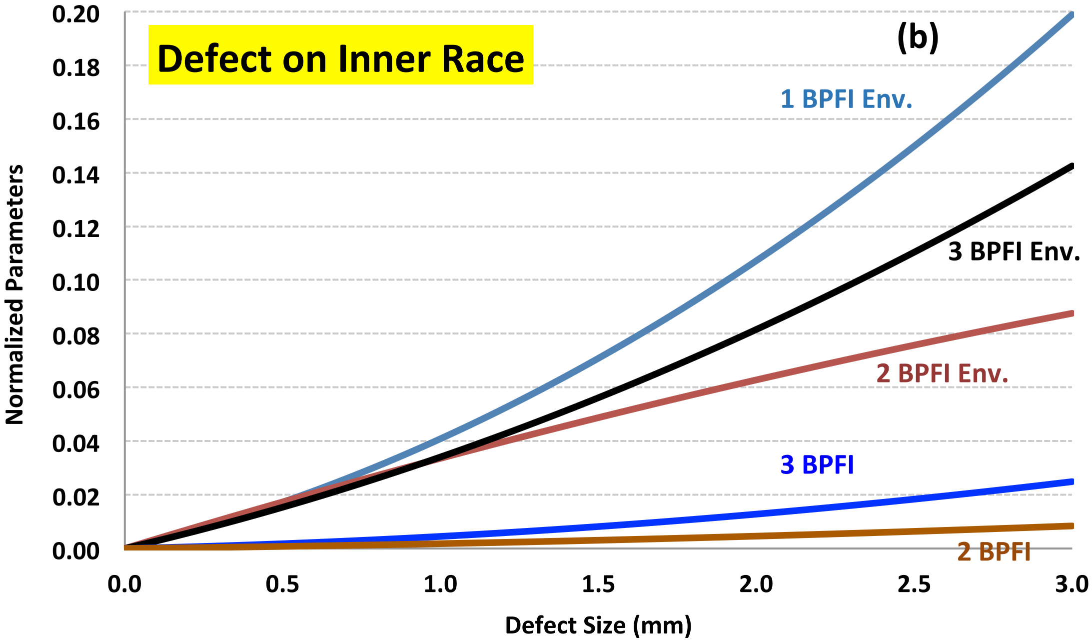


Figure 64: All harmonics of direct and enveloped spectrum: (a) Outer ring defects, (b) Inner ring defects

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

In this chapter, a summary of this research thesis is presented. The success of the research methodology is evaluated. Major findings and outcome are discussed. Future work in the area is recommended.

5.1 Conclusions

Rolling element bearings are essential components in any rotating equipment. Therefore, their condition monitoring is a vital task for any maintenance and production crew, to detect in an early stage any defects that may compromise the safe operations of their supporting machines. There are many techniques for the condition monitoring of rolling element bearings, such as acoustic emissions, vibration, oil analysis and temperature based monitoring. This study focuses on the vibration-based health monitoring method applied for bearings fault detection.

Because of its ability to detect early-stage degradation, vibration technique is receiving increasing attention from researchers and engineers. For health condition monitoring for rotating machines, vibration analysis is used as a fundamental and single method, and sometimes as a complementary technique for other procedures. This research presents an experimental study to investigate the vibration behavior of defective bearings based on parameters extracted from time and frequency domains.

During the first step of this work, a test rig was designed, manufactured and tuned to be used for data acquisition when a damaged bearing is installed on it. By deliberately seeding defects on the raceways of a deep-groove ball bearing, with different values of diameters, several experiments have been conducted to recognize the existence of those defects from the vibration signal and to quantify their extent based on several parameters extracted from time and frequency domains.

After trying to open the bearings to seed defects on the raceways by punching system, an Electrical Discharge Machine EDM was efficiently used for the first time. A National Instruments (NI) data acquisition card was used to collect the data. The control of the hardware was made by a specific code written in MATLAB programming language.

The defects sizes in this investigation range from 0.35 mm up to 3 mm. All tested bearings had the same lubrication, mounting and testing conditions. For each tested bearing, the experiment was repeated ten times to increase the reliability of the results (by minimizing their dispersion about their mean values).

In summary, the experiment had three inputs and one output. The inputs were: the defect size of the bearing, the rotational speed of the rotor and the applied load on the tested bearing, whereas the response vibration signal was the output of this experiment. The total number of experiments conducted on twenty-two bearings used in this study accounted for 220 trials overall. Each trial had the duration of ten seconds.

To track the evolution of defects, different parameters extracted from time-domain and frequency-domain were considered. These parameters showed an increase along with defect size but at different degrees of sensitivity. In time domain the most sensitive parameters were found to be the kurtosis and the peak amplitude. In addition to conventional time-domain parameters, commonly used by vibration practitioners, two new time-domain parameters were introduced. They were named as SIANA and INTHAR. Both of them demonstrated high sensitivity to the detection of growth in bearing defects sizes. In the frequency domain, the second and third harmonics of ball pass frequencies on inner and outer rings were found the most sensitive parameters. In general, the indicators extracted from the frequency domain seem to be more sensitive than time domain parameters to the evolution of degradation inside the bearing. This result is perhaps because the time domain signal accounts for the contribution of all vibration responses generated by all components of the machine. On the contrary, the information collected from the frequency domain represents the contribution of one single element, which is the bearing in this case.

The Envelope Detection (ED) was also used in this study as a possible technique to track the increase of damage inside bearings. Compared with direct spectrum, this approach allowed for better visualization of BPFO and BPFI. Furthermore, the use of ED was found to filter the electrical frequencies on the signal, which were hiding the real signature of defects.

In conclusion, among the three different methods studied in this study (i.e. statistical parameters in time domain, identification of bearing frequencies by FFT and envelope detection by the Hilbert transform), the method of envelope detection by the Hilbert transform is the best for the detection of bearing defect. In a real industrial environment that is by nature noisy with gears and other mechanical components, the time descriptors can’t be applied for the detection of bearing defects besides; they are only able to detect a fault without knowing its source. It is why the frequency descriptors are the only features able to detect bearing defects and the envelope is the best method since it may detect a defect at its early stage (stage 2). From this stage a closer attention shall be kept at the machine to track the degradation and avoid any catastrophic failure, since the deterioration in the bearing condition is faster after stage two and growing exponentially. This study has the potential to offer for vibration daily user a wide list of parameters that may be used as a control-dashboard for the early detection of bearing faults.

5.2 Future Work and Recommendations

The current study has focused only on the vibrational response of localized defects located exclusively on inner or outer rings of bearings. The following recommendations are suggested as future work extensions for this study:

- Consider the existence of simultaneous defects on outer and inner rings.
- Consider the measurement of different parameters simultaneously; vibration, acoustics and electric current.
- Consider the effects of lubrication type, load and rotational speed on the damaged bearing vibration response.

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