

Investigation into backup bearing life using delevitation severity indicators

JM Gouws
21662428

Dissertation submitted in fulfilment of the requirements for the
degree *Masters in Mechanical Engineering* at the
Potchefstroom Campus of the North-West University

Supervisor: Dr JJ Janse van Rensburg

October 2016

Acknowledgments

Firstly, I would like to express my gratitude towards Dr. Janse van Rensburg. Thank you being my supervisor and providing me with the necessary support, motivation and the opportunity to expand my knowledge beyond my own expectations.

Secondly I would like to thank Gert Kruger for always being willing to help me on numerous occasions regarding the active magnetic bearing system. Christian Vanek at the University of Applied Sciences for providing insight and presenting our paper at the 10th Workshop on Magnetic Bearings Technology in Zittau. Also to everyone at the McTronX research group for providing me with insight, friendship and moral support.

Finally, I would like to thank my parents and family who have lovingly and unconditionally supported me financially and emotionally throughout my academic career. Words could never express my gratitude for all the opportunities and support you have provided me with.

Abstract

Active magnetic bearings (AMBs) are inherently flawed in terms of possible failure from either mechanical, electronic or software components. Component failure could induce a rotor delevitation event (RDE) during operation and possibly damage the backup bearing (BB) system. To improve BB reliability and safety, the applicability of using quantified delevitation severity indicators *DVAL*, *VVAL* and *AVVAL* for quantifying degradation and predicting BB life is investigated.

A small-scale AMB system is used to generate BB degradation data by subjecting steel-caged rolling-element bearings to multiple RDEs. The RDEs are induced at specific initial conditions to analyse bearing failure distribution. Delevitation severity indicators are subsequently used to compare a series of RDEs to analyse changes in BB performance characteristics. Using only shaft position and rotating speed data, this investigation showed that delevitation severity indicators change as the bearing degrades.

A distinctive linear pattern of degradation is identified by calculating *AVVAL* for the duration when rotor whirl and bouncing occurs. A threshold value when BB failure occurs is also identified. Using the linear degradation pattern and identified threshold failure value, two life prediction methods are formulated: the safe envelope method (SEM) and the linear extrapolation method (LEM). The SEM and LEM were validated with successful life predictions at various initial conditions and provided an average prediction accuracy of 91%. The two methods were found to be applicable only when BB life exceeded that of the bearing's run-in phase.

Large and sudden changes in rolling friction were detected by calculating the values of *DVAL* and *AVVAL* for the duration when a rolling motion is induced. The changes serve as an early warning for possible catastrophic failure of the bearing and enable a form of BB failure detection. The failure detection capability was verified by uncovering the linear relationship between rolling friction and *AVVAL*. This linear relationship further shows that *AVVAL* is indicative of bearing degradation.

A novel method for quantifying rotor movement is obtained from *ADVAL*. This method enables critical frequency analysis of the BB system, identification of rotor delevitation severity, and forward or backward whirl detection capabilities. Different rotordynamic motions were found to depend on the rotor traversing specific critical frequencies of the AMB system. The magnitude of transverse movement was also found to be independent of the delevitation speed. Application of this method would be the comparison of rotor delevitation quality by various BB manufacturers for design and implementation purposes. This method also provides accurate verification of delevitation modelling by comparing simulated transverse movement to actual transverse movement

Recommended future work includes the integration of delevitation severity indicators in RDE modelling. The effect of BB support stiffness and damping on life prediction methods should further be studied. An investigation of the effect of cage-less ceramic or lubricated bearings on life prediction methods is also recommended. A method for determining the identified failure thresholds from basic system variables is also required.

Keywords: Backup bearing; Auxiliary bearing; Catcher bearing; Life prediction; Failure detection; Active magnetic bearing; Quantification, Bearing degradation

Contents

CONTENTS	I
LIST OF FIGURES.....	III
LIST OF TABLES	V
LIST OF SYMBOLS	VI
LIST OF ABBREVIATIONS	VII
CHAPTER 1.....	1
INTRODUCTION	1
1.1 PROBLEM STATEMENT	2
1.2 RESEARCH GOALS.....	2
1.3 SCOPE AND RESTRICTIONS OF RESEARCH.....	2
1.3.1 Scope	2
1.3.2 Restrictions.....	2
1.4 MAIN ISSUES TO BE ADDRESSED.....	2
1.4.1 Repeatable rotor delevitation method.....	2
1.4.2 Gathering backup bearing degradation data	3
1.4.3 Usability of delevitation severity indicators	3
1.4.4 Verification and validation.....	3
1.5 CHAPTER LAYOUT.....	3
CHAPTER 2.....	4
LITERATURE OVERVIEW	4
2.1 BACKGROUND ON MAGNETIC BEARINGS	4
2.2 BACKGROUND ON BACKUP BEARINGS	5
2.2.1 Rolling-element bearings.....	5
2.2.2 Bushing type bearings.....	6
2.2.3 Planetary type bearings	6
2.2.4 Zero clearance auxiliary bearings	6
2.2.5 Hybrid backup bearings	7
2.3 ROTOR-BEARING TOUCHDOWN DYNAMICS.....	7
2.3.1 Oscillating Motion.....	8
2.3.2 Bouncing motion	8
2.3.3 Forward whirl	9
2.3.4 Backward whirl	9
2.4 BACKUP BEARING DEGRADATION FACTORS	10
2.5 BEARING FAILURE CRITERIA	11
2.6 BACKUP BEARING LIFE PREDICTION IN LITERATURE.....	13
2.7 SUMMARY	14
CHAPTER 3.....	16
EXPERIMENTAL METHOD.....	16
3.1 INTRODUCTION	16
3.2 EXPERIMENTAL SETUP	16
3.2.1 Active magnetic bearing system specification.....	16
3.2.2 Rotor specification.....	17
3.2.3 Backup bearing specification	17
3.3 DELEVITATION SEVERITY INDICATORS	18
3.3.1 DVAL	18
3.3.2 VVAL	20
3.3.3 AVVAL	20
3.4 EXPERIMENTAL PROCEDURE.....	20

3.4.1	Degradation data acquisition process	21
3.4.2	BB failure detection methods	22
3.5	EXPERIMENTAL RESULTS	22
3.6	DISCUSSION	24
CHAPTER 4		26
QUANTIFYING BEARING DEGRADATION		26
4.1	INTRODUCTION	26
4.2	DEGRADATION QUANTIFICATION METHOD	26
4.3	DEGRADATION QUANTIFICATION RESULTS	28
4.3.1	Quantifying degradation for a series of full delevitations	28
4.3.2	Rotordynamic analysis using delevitation severity indicators	31
4.3.3	Quantify bearing degradation according to rotordynamic severity	35
4.3.3.1	<i>Case A: Life analysis during forward whirling and bouncing (BB life prediction)</i>	35
4.3.3.2	<i>Case B: Life analysis during oscillating motion</i>	38
4.3.3.3	<i>Case C: Life analysis during rolling motion (BB Failure detection)</i>	41
4.4	DISCUSSION	44
CHAPTER 5		45
USEFULNESS OF SEVERITY INDICATORS FOR LIFE PREDICTION		45
5.1	INTRODUCTION	45
5.2	SAFE ENVELOPE METHOD	45
5.2.1	Safe envelope method settling time	47
5.3	LINEAR EXTRAPOLATION METHOD	47
5.3.1	Linear extrapolation method settling time	50
5.4	DISCUSSION	51
CHAPTER 6		52
VALIDATION AND VERIFICATION		52
6.1	VERIFICATION	52
6.1.1	Relationship between AVVAL and rolling friction	52
6.1.2	Relationship between delevitation duration and DVAL	56
6.1.3	Critical frequency analysis verification	57
6.2	VALIDATION OF FAILURE DETECTION METHOD	59
6.2.1	Failure detection validation	59
6.3	VALIDATION OF LIFE PREDICTION METHODS	60
6.3.1	Bearing failure results summary	60
6.3.2	Safe envelope method validation	61
6.3.3	Linear extrapolation method validation	62
6.3.4	Average of SEM and LEM	64
6.4	DISCUSSION	64
CHAPTER 7		66
CONCLUSIONS AND FUTURE WORK		66
REFERENCES		68
APPENDIX A. CALCULATION EXAMPLES		72
APPENDIX B. ROTOR DELEVITATION RESULTS		79
APPENDIX C. ROTOR SPECIFICATIONS		103
APPENDIX D. RESEARCH OUTPUTS		104
D1. 15 TH INTERNATIONAL SYMPOSIUM ON MAGNETIC BEARINGS		104
D2. 10TH WORKSHOP ON MAGNETIC BEARINGS TECHNOLOGY		112
APPENDIX E. ELECTRONIC ATTACHMENT		121

List of figures

Figure 2-1: Diagram of basic AMB system layout [15]	4
Figure 2-2: Illustration of a planetary type BB system [23]	6
Figure 2-3: Illustration of a ZCAB [23]	7
Figure 2-4: Illustration of a rotor oscillating within the BB clearance	8
Figure 2-5: Illustration of a rotor bouncing within the BB clearance	8
Figure 2-6: Illustration of a rotor subjected to forward whirl within the BB clearance	9
Figure 2-7: Illustration of a rotor subjected to backward whirl within the BB clearance.....	10
Figure 3-1: Small-scale experimental test bench used for rotor delevitation	17
Figure 3-2: Rotor used for experimental delevitation	17
Figure 3-3: Diagram of the backup bearing system assembly	18
Figure 3-4: Graphical interpretation of the non dimensionalised distance (<i>DVAL</i>)	19
Figure 3-5: Example of a 3000 r/min RDE quantified using <i>DVAL</i>	19
Figure 3-6: Bearing degradation data acquisition process	21
Figure 3-7: Bearing failure distribution curve	23
Figure 3-8: Illustration of catastrophic bearing cage failure caused by multiple RDEs	23
Figure 3-9: Illustration of rotor orbit plots at bearing failure	24
Figure 4-1: Flowchart of degradation quantification method	27
Figure 4-2: Severity of a single delevitation quantified using <i>DVAL</i> , <i>VVAL</i> and <i>AVVAL</i>	29
Figure 4-3: Severity of 142 delevitations quantified using <i>DVAL</i> , <i>VVAL</i> and <i>AVVAL</i>	30
Figure 4-4: Degradation quantified using <i>DVAL</i> , <i>VVAL</i> and <i>AVVAL</i>	30
Figure 4-5: Degradation quantified for multiple delevitation conditions	31
Figure 4-6: Severity of rotor motion within various stages of rotor delevitation ($\Delta DVAL$).....	32
Figure 4-7: Illustration of rotor motion within various stages of rotor delevitation	33
Figure 4-8: Vibration analysis using $\Delta^2 DVAL$	34
Figure 4-9: Severity of a single delevitation quantified during a whirl and bouncing motion	36
Figure 4-10: Severity of 142 delevitations quantified during a whirl and bouncing motion	37
Figure 4-11: Degradation quantified during a bouncing and whirl motion	37
Figure 4-12: Degradation quantified during a bouncing and whirl motion for multiple conditions.....	38
Figure 4-13: Severity of a single delevitation quantified during an oscillating motion	39
Figure 4-14: Severity of 142 delevitations quantified during an oscillating motion.....	40
Figure 4-15: Degradation quantified during an oscillating motion.....	40
Figure 4-16: Degradation quantified during an oscillating motion for multiple conditions	41
Figure 4-17: Degradation quantified during a rolling motion.....	42
Figure 4-18: Degradation quantified during a rolling motion for multiple conditions	43
Figure 4-19: Failure detection of BBs using <i>AVVAL</i>	43
Figure 5-1: Failure zones of the safe envelope method for BB life prediction	46
Figure 5-2: Safe envelope method - prediction example	46
Figure 5-3: Safe envelope method settling time	47
Figure 5-4: Cumulative <i>AVVAL</i> after each RDE until bearing failure.....	48
Figure 5-5: Cumulative <i>AVVAL</i> after each RDE until bearing failure for multiple delevitation conditions.....	48
Figure 5-6: <i>AVVAL</i> failure curve	49
Figure 5-7: Linear extrapolation method linear fit example.....	50

Figure 5-8: Linear extrapolation method settling time.....	51
Figure 6-1: Change in bearing friction over a series of RDEs	53
Figure 6-2: Effect of bearing friction on delevitation duration and transverse movement	53
Figure 6-3: Relationship between <i>AVVAL</i> and bearing friction	54
Figure 6-4: Bearing damage - Scanning electron microscope images	55
Figure 6-5: Non-dimensionalised distance (left) and delevitation duration (Right) for each RDE of a bearing subjected to 142 RDEs at 4000 r/min until failure	56
Figure 6-6: Relationship between delevitation duration and <i>DVAL</i>	56
Figure 6-7: Relationship between delevitation duration and <i>AVVAL</i>	57
Figure 6-8: $\Delta DVAL$ critical frequency analysis.....	58
Figure 6-9: Spectral decay plot critical frequency analysis.....	58
Figure 6-10: Failure detection validation.....	59
Figure 6-11: Inspection of bearings at suspected failure.....	60
Figure 6-12: Rotordynamic analyses of different manufacturer bearings.....	61
Figure 6-13: Safe envelope method validation results	62
Figure 6-14: Linear extrapolation method validation results	63

List of tables

Table 2-1: Summary of rolling element bearing failure criteria [40 - 45]	12
Table 3-1: Bearing failure results at various delevitation speed	22
Table 4-1: Capability comparison of delevitation severity indicators	44
Table 6-1: Bearing failure results summary	60
Table 6-2: Safe envelope method prediction results summary.....	62
Table 6-3: Linear extrapolation method prediction results summary.....	63
Table 6-4: Optimized prediction (average of SEM and LEM).....	64

List of symbols

Symbol	Description
α_{Rotor}	Rotational acceleration of the rotor [$r. s^{-2}$]
$AVVAL$	Average non dimensionalised acceleration [s^{-2}]
$DVAL$	Average non-dimensionalised distance [—]
D_n	Delevitation number [—]
E_k	Kinetic energy [J]
F	Force [N]
g	Gravitational acceleration [$m. s^{-2}$]
i	Index number
I	Impulse [N. s]
I_{Rotor}	Polar moment of inertia of rotor [mm^4]
k	Index number equal to predefined value lower than first system critical frequency
m	Mass [kg]
t	Time in minutes [min] or seconds [s]
μ	Friction coefficient [—]
ω	Rotational speed [r/min]
r_{airgap}	Radius of backup bearing/rotor airgap [m]
$\tau_{friction}$	Braking torque due to friction [N. m]
v	Velocity [$m. s^{-1}$]
$Vval$	Average non-dimensionalised velocity of the rotor [s^{-1}]
x	Rotor position from backup bearing geometric centre in the x-direction [m]
y	Rotor position from backup bearing geometric centre in the y-direction [m]

List of abbreviations

AMB	Active magnetic bearing
BB	Backup bearing
LEM	Linear extrapolation method
PMB	Passive magnetic bearing
RDE	Rotor delevitation event
SEM	Safe envelope method
ZCAB	Zero clearance auxiliary bearing

Chapter 1

Introduction

Since the dawn of rotating machinery, some of the key design factors in many applications have been performance, efficiency and reliability. The principle components of these rotordynamic systems are usually the shaft, bearings and the seals. The bearings support the rotating components of the system and usually provide the damping needed to stabilize and contain vibrations induced by the rotor. If rotordynamic problems are not monitored and maintained, the bearings are susceptible to failure that could result in serious damage to the system [1]. It is no surprise that over the past few decades numerous research, design and development projects have been conducted to improve bearings in all aspects and applications.

A very unique development in the field of bearing technology is active magnetic bearings (AMBs). AMBs allow levitation of the rotor using magnetic fields, which brings forth unique and innovative solutions to classic rotordynamic problems. Problems associated with lubrication, friction, wear and dynamic behaviour control can easily be solved with AMBs [2, 3].

Safe and continuous operation of an AMB system relies heavily on its mechanical, electronic and software components. If one of these components fails, a rotor delevitation event (RDE) could be induced. Schweitzer states *“Safety is the quality of a unit to represent no danger to humans or the environment when the unit fails.”* [4]. To increase the safety and reliability aspects of AMB systems, they are fitted with backup bearings (BBs) that protect the AMB stator components if an RDE were to occur [1, 5].

The dynamics of RDEs are non-linear and often result in loads exceeding that of rated bearing load [4]. Numerous mathematical tools and models have been developed to predict rotor behaviour during an RDE [6]. These modelling techniques however largely neglect the effect of individual delevitations on overall BB life. Standard bearing life prediction methods such as those presented by Lundberg-Palmgren [7] do not apply to the non-linear load conditions to which BBs are mostly subjected to [8]. The life prediction methods that directly apply to BB systems are highly simulation based and rely on the knowledge of various system specific parameters. Implementation of these methods on commissioned AMB systems is unsatisfactory due to the need of predetermined and assumed initial conditions. The existing methods are also computationally intensive and lack the ability to quantify the degradative properties of individual RDEs as to predict the ultimate BB life. The initial conditions of subsequent RDEs are rarely identical and may differ in terms of their destructive behaviour towards the BBs. It is currently believed to be beyond state of the art to precisely predict rotor behaviour and BB life [9].

A study conducted by Reitsma suggested that only shaft-delevitation position and BB clearance monitoring after an RDE yields potential for BB predictive maintenance capabilities [10]. In 2014, Janse van Rensburg submitted a thesis presenting a method for quantifying the severity of an RDE using only position and velocity data. The delevitation severity indicators presented can be used to quantify and compare subsequent RDEs to infer changes in BB performance characteristics [11, 12]. The energy dissipated by the BBs during an RDE is an indication of the degradation of bearing quality

caused by delevitation of the rotor [11]. Considering the conclusions by Reitsma, the usability of delevitation severity indicator for BB life prediction and degradation quantification is investigated.

1.1 Problem Statement

The life prediction of backup bearings is poorly described in current literature with few reliable methods for quantifying backup bearing life under various conditions. To develop a backup bearing life prediction method for the AMB system of the North-West University, quantified backup bearing degradation data are required. The problem therefore is a lack of available backup bearing degradation data and the lack of a life analysis based on this data for an AMB system.

1.2 Research goals

The primary focus of this research is to investigate the usefulness of rotor delevitation severity indicators for quantifying BB degradation. These indicators will be used to develop a method for predicting BB life based on repeated rotor delevitations. The secondary objective of this research is to obtain suitable BB degradation data using an experimental setup for future simulation-based research projects.

1.3 Scope and restrictions of research

The following lists define the scope and main restrictions of this research.

1.3.1 Scope

- An active magnetic bearing system will be used to gather BB degradation data.
- The developed life prediction method should be based on delevitation position and velocity data.
- Due to the lack of active magnetic bearing systems found in continental boundaries, the developed life prediction method should apply to the available experimental setup.
- A target life prediction accuracy of 80% is required for the developed life prediction method

1.3.2 Restrictions

- The rotor used during the course of this research is horizontally suspended using AMBs. The gathered BB degradation data will thus be limited to radial delevitations.
- The BB holders are assumed to be rigidly mounted due to the lack of added damping support.
- The effect of damping and support stiffness on the developed life prediction method will not be investigated.
- A BB life prediction method will be developed to apply to rolling element type bearings.

1.4 Main issues to be addressed

The following is a short summary of the main issues to be addressed during the course of this research.

1.4.1 Repeatable rotor delevitation method

To have comparable rotor delevitation results, a method for inducing multiple repeatable rotor delevitations is required. This involves the design, implementation and testing of a new BB holder system.

1.4.2 *Gathering backup bearing degradation data*

By inducing multiple RDEs at various initial conditions, BB degradation data are generated. The delevitation data for various delevitations are recorded until noticeable BB failure occurs. This is done to find a statistical BB failure distribution and further investigate the need for a life prediction method.

1.4.3 *Usability of delevitation severity indicators*

Using the gathered experimental delevitation data, delevitation severity indicators will be used to compare various RDEs to investigate BB degradation patterns. The quantified degradation data will then be analysed for distinctive trends and/or threshold failure values usable for life prediction purposes.

1.4.4 *Verification and validation*

The developed life prediction method will be validated with experimental delevitation results. Verification of delevitation severity indicators as a tool for quantifying degradation will be verified by studying the relationship between delevitation severity indicators and rolling friction.

1.5 Chapter layout

The following list presents a short summary of the dissertation layout.

Chapter 2 contains a literature overview on AMBs, BBs, rotor-bearing touchdown dynamics, BB failure criteria and previous research regarding BB life prediction.

Chapter 3 discusses the methodology applied during the course of this research. This chapter contains information on the experimental AMB system, and method used for gathering BB degradation data. The delevitation severity indicators used to quantify BB degradation are additionally discussed. An in-depth analysis of experimental rotor delevitation results are also shown. This analysis includes an investigation into BB failure distribution, BB failure modes and failure detection methods applied to identify BB failure.

Chapter 4 covers the main topic of the research presented within this dissertation. An investigation into the usability of delevitation severity indicators for quantifying degradation is made. This investigation includes the method used to quantify degradation, a rotordynamic analysis using delevitation severity indicators and degradation quantification results. An investigation into the use of delevitation severity indicators for life prediction purposes is also presented.

Chapter 5 presents two methods for predicting BB life based on the results obtained in Chapter 4. The methods are formulated and discussed to identify shortcomings and capabilities.

Chapter 6 discusses verification of delevitation severity indicators as a means of monitoring BB degradation. Validation of the developed life prediction methods is included within this chapter.

Chapter 7 presents conclusions regarding the research presented in this dissertation. Recommendations for future research work are additionally discussed.

Chapter 2

Literature overview

This chapter contains a basic discussion within the field of magnetic bearings. This discussion includes information on backup bearings, rotor-bearing touchdown dynamics, and an investigation into backup bearing life prediction as found in literature. Bearing failure criteria are additionally investigated.

2.1 Background on magnetic bearings

Magnetic bearings are a relatively modern concept in terms of bearing technology. These bearings make use of magnetic forces to levitate and support a rotor mid-air without any contact to the stator assembly [2].

When it comes to magnetic levitation of a rotor, two possible configurations are commonly used. The first configuration is known as passive magnetic bearings (PMBs), wherein levitation is achieved using permanent magnets. The other configuration is known as active magnetic bearings (AMBs), wherein levitation is achieved using electromagnets [13].

Purely passive magnetic suspension has been found to be physically impossible since at least one degree of freedom will always be unstable. These unstable degrees of freedom need to be controlled actively, either by means of permanent magnets, mechanical bearings, or some other form of active control [2, 14]. AMB systems requires a control loop for stable suspension and conceptually consists of magnetic actuators, electronic controllers, power amplifiers, and shaft position sensors [15]. Figure 2-1 shows the basic layout of these components:

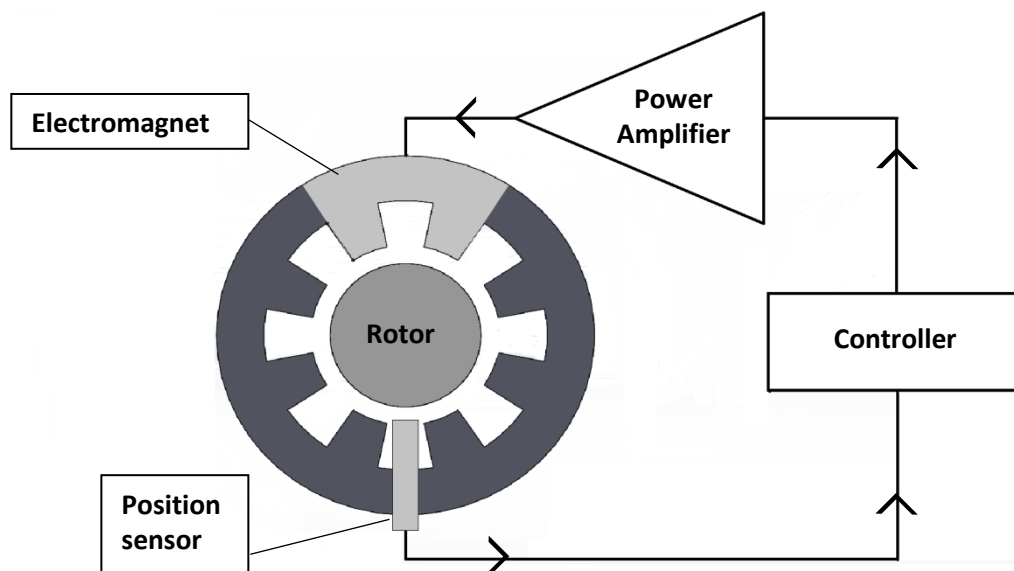


Figure 2-1: Diagram of basic AMB system layout [15]

AMBs are unstable in an open-loop system and require closed-loop feedback control for stable levitation. The objective of feedback control is to maintain rotor levitation at the geometric centre or some other predefined location within the AMB clearance [16]. The position sensor measures the

rotor position from a predefined reference location. This position signal is sent to a controller from which a control signal is derived to correct any error in position measured from the predefined reference position. The control signal is sent to a power amplifier that generates the current required by the electromagnets to keep the rotor levitated at the reference position [2]. This process is constantly repeated at a certain sampling frequency that is dependent on the AMB system specifications.

One problem faced with AMB technology; is the fact that when the system is shut down, overloaded, or power supply to the electromagnets are interrupted, a rotor delevitation event (RDE) could occur [17]. This is a major disadvantage of AMB technology since auxiliary support for the rotor has to be provided in case of such an event. Further complications of such an event includes possible rotor damage, complicated installation of auxiliary support systems in existing conventional bearing systems and increased costs [2]. This auxiliary support usually comes in the form of a backup bearing (BB) system of which numerous combinations and permutations of these BB systems exist. Some BB solutions will now be discussed.

2.2 Background on backup bearings

Backup bearings (BBs) are an essential part of any AMB system since they serves as the last line of defence in protecting the internal components during an RDE. The clearance of BBs are typically half of the AMB airgap [1, 18 - 20]. This distance ensures that no contact between the rotor and the BBs exists when the AMBs are activated. BBs not only prevents possible damage to the stator and rotor assemblies during an RDE, but also assist in safely containing rotor vibrations mechanically when the AMBs are not able to keep the rotating components stable [1, 5]. Furthermore, BBs serve as a platform for the rotor to rest on when the AMBs are not in use. The bearings allow the rotor assembly to be rotated manually for inspection and maintenance purposes [1 - 3] .

BBs are subjected to high transient loads during an RDE and are usually not designed to be operated for long periods of time [1]. Results have shown that rotor-bearing touchdown dynamics are extremely difficult to predict since numerous system parameters and variables influence the behaviour of the rotor during an RDE. The difficulty to predict rotor behaviour makes rotor delevitation modelling an active topic of research in many institutions [2, 5]. The selection of BBs are largely dependent on specific application and operating conditions of the AMBs [2]. Experience plays a vital role in the selection process, since inappropriate selection and a lack of knowledge could result in fatal consequences for the rotor during an RDE [21].

The various types of BBs available can be categorised into three main groups: bushing type bearings, rolling-element bearings and planetary type bearings [1, 5]. Other types of BBs include zero clearance auxiliary bearing (ZCAB), and hybrid backup bearings [1]. Each of these will be discussed separately.

2.2.1 *Rolling-element bearings*

Rolling-element bearings (radial contact and angular contact) are the most commonly utilized BB solutions for industrial applications [1, 2, 12, 22]. Angular contact bearings are used more often than radial contact bearings [1 - 3, 15, 22]. The angular contact design allows both radial and axial loads to be applied to the bearing since axial forces are usually present within the system. The angular contact design also allows the application of a preload to the bearing that effectively increases the

stiffness of the bearing. This increased stiffness of the bearing not only allows it to withstand a greater amount of shock landing in the axial direction, but also increases the rolling resistance of the bearing [22].

Advantages of using rolling-element bearings include the choice of simple standardized designs, lower costs for certain low-speed applications, low friction coefficients and low heat generation. Disadvantages include increased costs for higher speed applications, difficult condition monitoring of the bearing, and a short operating time in rapid spin-up applications [23].

2.2.2 *Bushing type bearings*

These types of bearings are usually the simplest form of BB systems and mostly consist of only plain sleeves. Material selection of these bearings is highly dependent on the application under consideration and typically consists of soft materials such as bronze, Babbitt-lined or graphite-alloy materials [5]. By implementing a softer material, the chance of damage to the rotor during an RDE is minimized. More complicated configurations, making use of compliant mounts to minimize the effects of rotordynamics during an RDE also exist [23].

Advantages of these types of bearings include simplicity in design, the ability to easily monitor its condition without removal and lower cost compared to other types of BBs. Due to the high friction coefficients of these types of bearings, provision has to be made to dissipate the heat from the system and minimize the effect of thermal growth [23].

2.2.3 *Planetary type bearings*

Planetary type bearings can be considered when large-diameter BBs and high-speed rotation are required [5, 23]. They are composed of three or more separate rolling elements in a circular configuration around the rotor. The rolling elements are fixed and kept in position by a large separate external ring surrounding the rotor. Figure 2-2 shows a basic illustration of this BB system.

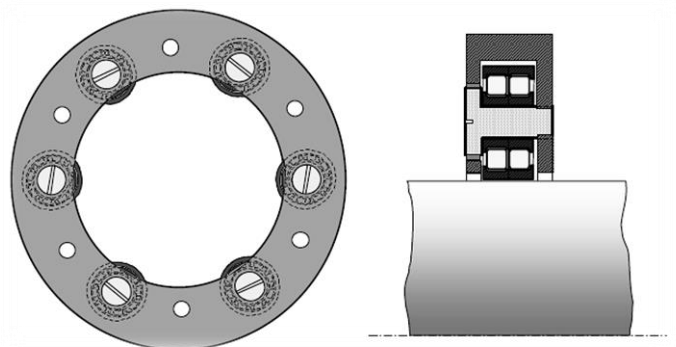


Figure 2-2: Illustration of a planetary type BB system [23]

2.2.4 *Zero clearance auxiliary bearings*

ZCABs are a specialized design of planetary type bearings [1, 5]. As in planetary type bearings, the rolling elements are placed in a circular configuration within a retainer ring around the shaft. As soon as an RDE occurs, the rolling elements within the ZCAB moves on a curved path within the circular retainer ring, eliminating the clearance between the shaft and the BB. This automatically centres the shaft within its initial position [24, 25]. Figure 2-3 shows an illustration of a ZCAB.

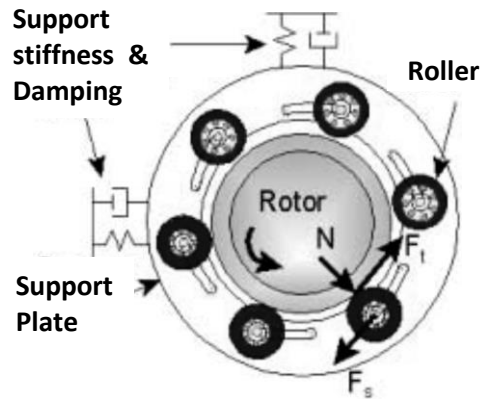


Figure 2-3: Illustration of a ZCAB [23]

The main advantage of this type of BB is removing the clearance between the BB and the rotor shaft during an RDE. This reduces the chance of destructive backward whirl occurring and increases the service life of the bearing. It also addresses various issues associated with other types of BBs such as cage instability, ball skidding and high rotation speed [25]. Disadvantages of these bearings include increased complexity and cost in comparison with other types of BBs. The complexity in ZCAB design creates additional challenges such as sensitivity to contamination and potential for acceleration damage [1].

2.2.5 Hybrid backup bearings

Hybrid BBs include various combinations and permutations of the BB support previously discussed within this section. Mechanical ball bearings can be incorporated using steel races, ceramic balls, and grease compatible for the use within a vacuum [26]. In other instances, tests were done using self-acting hydrodynamic bearings [25]. The air-lubricated hydrodynamic bearing allows load sharing with the AMBs which not only increases the total load capacity of the system, but also provides low-friction support during an RDE. A major problem associated with these hydrodynamic bearings is the very low load capacity at low shaft speeds.

2.3 Rotor-bearing touchdown dynamics

When loss of magnetic bearing function occurs, transient or persistent contact between the BBs and magnetically suspended rotor could be induced resulting in large-amplitude vibration [15]. Understanding rotordynamic behaviour during an RDE is an essential aspect in the design and implementation of reliable BB systems [15]. The touchdown process between a rotor and BB system is distinctly characterised by four different phases of motion within the BB clearance [27]. These phases of motion include rotor free fall, impact, sliding and rolling. Depending on the initial conditions and the BB system characteristics, the rotor can also be subjected to different dynamic states within the BB clearance. These states can be one, or a combination of the following motions: an oscillating motion in the bottom of the BBs, bouncing of the rotor within the BB clearance, forward whirl of the rotor, or backward whirl of the rotor [2, 28, 29].

The dynamic states of the rotor can be visually represented using an orbit plot. An orbit plot shows the motion of the geometric centre of the rotor within the BB clearance during both levitation and

delevitation of the rotor. To understand the cause and the effect of different rotordynamic states on a BB system, each one will be discussed. The orbit plots found in the following sections were experimentally determined from delevitation data. These orbit plots were compared to the work by Schweitzer [2] for verification purposes.

2.3.1 Oscillating Motion

An oscillating motion within a BB is widely agreed to be the most favourable dynamic response during an RDE [6, 30]. It is characterised by a rocking motion within the bottom of the BB and is usually present in well-designed BB systems where the unbalance forces are relatively low in comparison with that of the static load [27]. Figure 2-4 shows a typical orbit plot of an oscillating motion.

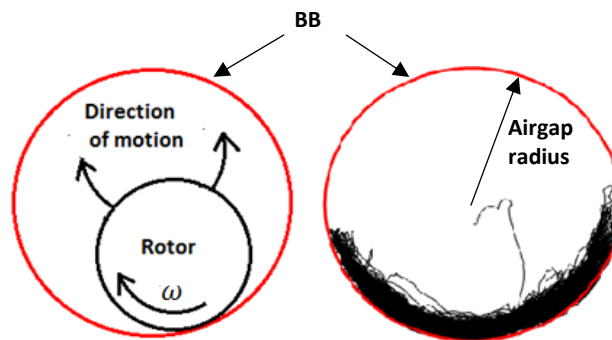


Figure 2-4: Illustration of a rotor oscillating within the BB clearance

The frequency at which the rotor oscillates within the BB clearance is dependent not only on the initial conditions of the delevitation (rotor speed and delevitation angle from bearing centre), but also the friction coefficient present within the system [27]. At higher speeds and in systems where lower damping is present, a bouncing motion could occur and is deemed more destructive towards the BBs [12].

2.3.2 Bouncing motion

Figure 2-5 contains the orbit plot of the rotor jumping chaotically within the BB clearance. The rotating shaft changes its rotational motion into translational motion between non-contact and contacting states. The observed bouncing motion is associated with the impact forces between the rotor and the BB. This chaotic behaviour is more destructive towards the BBs than an oscillating motion [12].

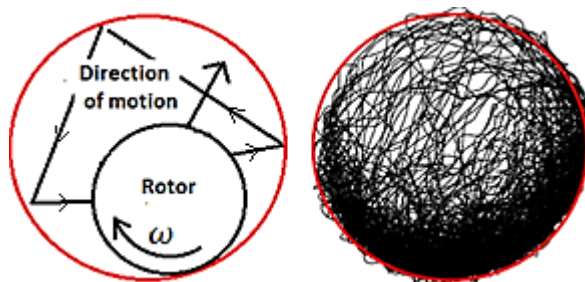


Figure 2-5: Illustration of a rotor bouncing within the BB clearance

Depending on the rotational frequency and friction coefficient present within the system, the rotor could enter a whirling motion after a series of impacts had occurred. This is where the rotor makes permanent contact with the bearing inner-race and large centrifugal forces are created [15]. This will now be discussed.

2.3.3 Forward whirl

Figure 2-6 contains an orbit plot of a rotor subjected to forward whirl within the BB clearance. The rotor's direction of rotation is in the same direction as the rotor's direction of motion during forward whirl [2]. A forward whirl motion is considered more destructive towards the BBs than an oscillating and/or bouncing motion [12]. The large centrifugal forces generated mainly causes the increased destructive properties of a forward whirling motion [2].

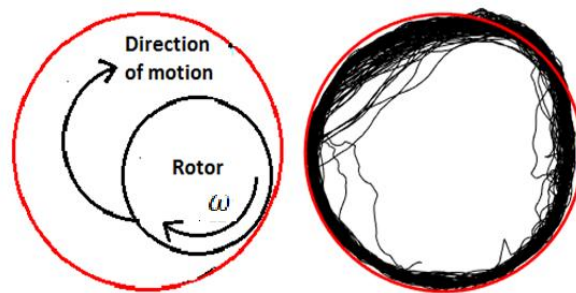


Figure 2-6: Illustration of a rotor subjected to forward whirl within the BB clearance

There are various factors contributing towards the occurrence of forward whirl. Hawkins et al. [31] found that increased unbalance on a rotor pushes the rotor from a rocking/oscillating motion into a full forward whirling motion. This usually occurs when unbalance forces are larger than the static load [32]. Forward whirl is dependent on the coefficient of friction [5], which corresponds to the results found by Wilkes et al. [33]. Additionally Wilkes et al. [33] showed that a forward cross-coupled force is responsible for pushing the rotor in the direction of rotation. This cross-coupled force is a result of friction between the bearing journal and the axial face of the bearing. The force is proportional to that of the axial thrust force on the rotor and the coefficient of friction between the rotor and BB's axial face. This force creates constant frequency whirl when the rotor speed is above a whirl frequency and synchronous whirl when rotor speed is below a combined natural frequency of the rotor-bearing system.

2.3.4 Backward whirl

An orbit plot during a typical backward whirl event is shown in Figure 2-7. Reported experimental and simulation results have shown that backward whirl is the most violent of all the motions that might occur during an RDE [2, 34]. The shaft rotating in the opposite direction of the whirling motion characterizes backward whirling.

The rotor delevitation speed has a considerable influence on the bearing load during backward whirl. Friction forces transferring energy from the shaft rotational speed into the backward-whirling motion causes increased centrifugal forces. BB loads during backward whirl increases with a larger airgap radius. This larger airgap radius creates an increased whirl radius effectively increasing centrifugal forces [28]. Large friction coefficients are one of the main causes of backward whirl and are usually caused by rubbing or very large bearing loads. The frequency at which backward whirl

occurs is usually confined to the lowest natural frequency of either the BB support system, or the spin frequency of the rotor. To counter this problem, BBs are installed in compliant mounts to increase damping properties of the system that effectively lowers the frequency at which whirling could occur [32].

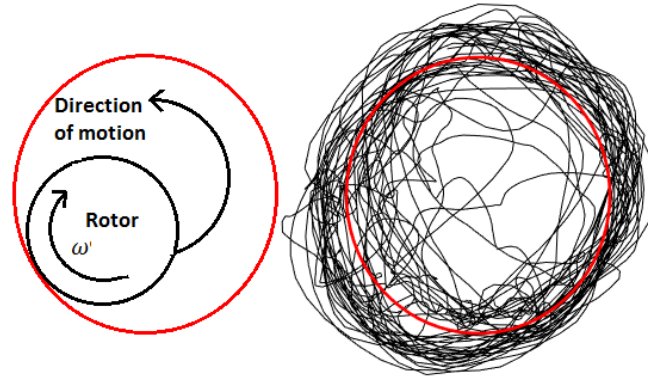


Figure 2-7: Illustration of a rotor subjected to backward whirl within the BB clearance

2.4 Backup bearing degradation factors

Due to the nature of delevitation events, BBs are often subjected to conditions and forces that exceed normal bearing design conditions and application. This non-standard application of the bearings, especially rolling-element bearings causes the bearing to have a much lower service life than the original bearing rated life [35]. The various non-standard factors present during an RDE degrade the bearing beyond its original standard service degradation. In this section various factors that contribute towards BB degradation are discussed. The following list shows a few of the main factors that decrease BB life.

- Centrifugal force [12]
- Bearing deformation [12]/ Impact load from delevitation transient [35]
- Impact loads from the rotor traversing through the clearance space [12, 26]
- Rated speed of the bearing [12] / Rapid spin-up and heating of bearing inner-race [35]
- Misalignment [35, 36]
- Damping [37]
- Stiffness [37]
- Rotor imbalance [32]
- High contact friction between bearing and rotor [5, 32]
- Operation near the first critical frequency [32]

The centrifugal force of the rotor is a function of the mass of the rotor, the speed at which the centre of mass of the rotor rotates within the BB clearance and the radius at which the rotor orbits at midpoint [12]. Jung Gu Lee [8] showed that BB life can be increased by decreasing the rotation speed of the rotor. The speed at which the rotor rotates directly influences the centrifugal force of the rotor. Backward or forward whirl significantly increases the centrifugal force. The increased centrifugal forces could subject the bearings to loads exceeding that of the rated bearing loads [2].

When an RDE occurs, a force generated by the deformation of the bearing exists. The stiffness, damping and position of the rotor with reference to the BB all contribute towards this generated

force [12]. By reducing the support stiffness and increasing the damping of the bearing, an increased BB life can be obtained [8].

Impacts caused by the rotor traversing within the BB clearance space degrade the bearing in a manner that is dependent on the initial conditions of the delevitation event. The impact caused by the traversing motion can differ in severity because the rotor could have a rocking/rolling motion, a bouncing motion or enter forward or backward whirl. A rocking/rolling motion is ideal and has the least effect on bearing degradation [12]. Forward whirl can occur if the static load is smaller than the unbalance forces [32], whereas destructive backward whirl can occur in cases of very low stiffness and high damping, or if high friction coefficients are present [37]. By reducing the BB airgap the BB life can be increased [8]. A smaller airgap reduces the impact force and impulse generated during an RDE by reducing the distance travelled by the rotor within the BB clearance.

Depending on the configuration and type of BBs set in place, a spinning rotor delevitating onto BBs causes the BB inner-race to rapidly accelerate from a stationary state up to the rotor operating speed. This rapid acceleration of the bearing inner-race is also known as spin-up [38]. All rolling-element bearings have a maximum speed at which they are rated to continuously operate without the risk of damage. For instance when a rotor is delevitated onto ball bearings (common BB solutions), the inner-race of the BB system engages causing rapid acceleration together with high friction and impact forces. These impact and friction forces sometimes exceed that which the bearing is rated for and cause the balls and races to be subjected to possible damage and skidding [3]. The longer the bearing inner-race takes to spin-up to the rotor speed, the more skidding present within the system. Increased skidding shortens the life of the BBs in high-speed applications [38]. By decreasing the contact friction coefficient between the rotor and the inner-race of the bearing, the life of the BB is increased [8].

Misalignment of the BBs has a significant effect on rotordynamic behaviour during an RDE. The effects of misalignment on BBs have been studied by varying the locations of the BBs in both the vertical and horizontal directions. Misalignment in the vertical direction has very little to no effect on the behaviour of the rotor during an RDE, which, in contrast to the horizontal direction, could induce a whirling motion if the misalignment is large enough. The whirling motion causes the rotor to revolve at high frequencies that could damage not only the BBs, but also the rotor [36]. A secondary effect of misalignment causes the axial contact to become more eccentric. The increased eccentricity of the axial contact if compared to the results found in [33], attributes to the occurrence of forward whirl.

2.5 Bearing failure criteria

Due to the highly destructive nature of RDEs, various types of damage might occur within the BB components. The American petroleum institute (API) standard 617 [39] considers BBs to “*be a consumable machinery protective device*” with specific BB performance and analysis requirements.

The API is intentionally vague on the analysis requirements since BB performance is likely to be AMB and vendor specific. This vagueness indicates that a general lack in consensus regarding BB analysis exists. Testing of the BB system is usually required where the life and the failure modes of the BBs might almost purely be established based on multiple system specific delevitation results. This gives

indication that the mode of BB failure is rather trivial as long as the specified requirements are met [9].

Bearing damage can be identified by a wide range of phenomena and is primarily identified by unusual system operating behaviour [40]. Bearing failure is rarely induced by a single cause and usually occurs due to a combination of factors [41 - 43]. Reitsma [10] suggests several main causes of BB failure. The main causes of BB failure can be one or a combination of corrosion, false brinelling, true brinelling, raceway spalling, fretting, misalignment, contamination, overheating and/or inadequate lubrication. Table 2-1 provides a description of some common bearing damage types.

Table 2-1: Summary of rolling element bearing failure criteria [40 - 45]

Bearing damage type	Cause of damage	Identification of damage
Wear	- Entry of debris - Poor lubrication - Sliding caused by irregular rolling element motion	- Deterioration of surface due to sliding friction of rolling elements, raceway, cage pockets etc.
Pitting and Bruising	- Poor lubrication - Lubricant contamination by debris - Atmospheric moisture exposure	- Dull indentations on bearing rolling-elements and raceway surfaces
Lubrication failure	- Lubrication starvation - Wrong lubricant for speed and load - Inadequate lubricant system	- Rolling element and raceway discoloration. - Excessive wear - Catastrophic failure/Bearing seizure
Normal fatigue failure/spalling	- Misalignment - Loading exceeding designed limits/excessive preload - Inadequate lubrication	- Increased machine vibration - Fracture of bearing running surfaces - Material removal from fractured surface in flake or scale like pattern
Damaged bearing cages or retainers	- Bearing misalignment - Poor handling - Shock loading and large vibration - Sudden acceleration and deceleration - Poor lubrication	- Fracture and deformation of bearing cage - Deformation of side face - Wear of cage pocket surface
Fretting	- Loose fit bearings - Relative motion between bearing outer-race and housing - Poor lubrication	- Reddish brown discolouration on bearing surface caused by worn particles
Scoring	- Excessive preload - Metal to metal contact - Tightly fit bearings - Sudden change in lubrication conditions	- Linear damage appearing circumferentially on bearing runway surfaces - Cycloidal shaped damage on rolling-elements
False brinelling	- Repeated vibration with a small oscillating angle	- Material wear and/or removal - Axial indentations

	- Inadequate lubrication distribution - Vibration in a static bearing	- Circumferential indentations - Roller indentations
True brinelling	- Radial shock load - Force incorrectly exerted	- Thrust indentations - Radial indentations

It is important to note that Table 2-1 only shows the bearing damage types expected to occur with multiple induced RDEs and are based on typical BB operating conditions. Very few sources specifically address BB failure criteria. Other bearing damage types do exist and might occur, but are not discussed for the purposes of this research.

2.6 Backup bearing life prediction in literature

This section contains an investigation on previous research done in the field of predicting BB service life. Various studies characterising the transient response during an RDE exist with little to no consideration towards BB life prediction. Some standards such as the API [39] provides guidelines towards the minimum allowable full speed RDEs until failure. Even though these standards exist, very few studies quantifying the effect of multiple RDEs on BB performance and life exist. Predicting the life and precise behaviour of the rotor is believed to be beyond state of the art [9].

Research presented by Lundberg-Palmgren [7], Ioannides-Harris [46] and Zaretsky [7] all yield the ability to estimate bearing life based on the load and environmental conditions of a bearing. Even though these methods are commonly used, they rely on manufacturer-specific data sheets and do not apply to the non-linear load conditions to which BBs are mostly subjected to.

The modified bearing life calculation as given by ISO 281 [47] can be used for bearing comparison and sizing purposes and provides reasonable functionality regarding a suitability check of BB designs [10]. This formula however is inadequate for BB life prediction purposes since the non-linear load conditions cannot be considered. Furthermore, the life adjustment factors used within this method are heavily dependent on operating temperature, lubrication conditions, types of impact loading and bearing materials.

A development program was undertaken by Reitsma [10] to develop a long-life BB system capable of withstanding multiple delevitations for critical-service turbomachinery and high-speed motors. This program included the development of modelling tools, simulation tools, identification, testing and optimization of full-scale test setups. Amongst various other results, it was found that all the failure detection methods used during the investigation were able to identify when a BB failure had occurred. Although not specifically shown, it was also concluded that the only method showing true potential for predictive maintenance is by using shaft-delevitation position data and BB clearance monitoring after an RDE.

Janse van Rensburg [6, 12] presented a method for characterizing rotor delevitation severity based on rotor behaviour within the BB clearance. By using velocity and position data acquired during an RDE, the author was able to formulate a quantitative value that can be used to compare various RDEs with each other. This quantitative value was verified with experimental results on a 4-axis suspended rotor with rolling-element BBs together with simulated results obtained from a BBSim model as presented in the author's previous work [12].

Sun [48] presented a method of estimating the fatigue life of BBs using a Hertzian-contact bearing model. The bearing fatigue life is calculated through the dynamic loads between the bearing ball and races during an RDE. By using a one-dimensional thermal model, the thermal growths can be predicted. In his research, a Lundberg-Palmgren formula was utilized. This formula is only valid for steady continuous loading which does not always reflect real-world BB conditions. Through his research, Sun found that BB life is significantly reduced with the occurrence of high-speed backward whirl and that optimal damping increases BB life by reducing BB temperature.

Lee [8] utilized a Rainflow counting algorithm to evaluate the fatigue life of BBs in terms of the number of delevitation events that could occur before BB failure. This research involved calculating the contact load, sub-shear stress, Hertzian stresses, thermal growths and surface shear stress. In his investigation, he found that reduced contact friction, decreased bearing airgap, decreased operating speed, lowered support stiffness and increased damping all contribute towards increased BB service life. He also found that large imbalance increases the possibility of forward whirl. Although preliminary predictions can be made, no condition monitoring capabilities are discussed and the effect of the bearing cage quality is not considered.

The following list shows the limitations of the methods discussed within this section.

- Standard bearing life prediction methods do not apply to BBs
- Limited to no condition monitoring capabilities
- Relies on the knowledge of various AMB and BB system parameters
- Complex calculations
- Highly simulation-based
- Bearing manufacturing quality is not considered

2.7 Summary

This chapter presented basic information on AMBs, BBs, rotor-bearing touchdown dynamics, factors contributing towards BB degradation and BB life prediction as currently found in literature.

In Section 2.2 it is found that rolling-element BBs are most commonly used in industrial applications. Considering the advantages associated with these types of bearings and the large amount of experimental data that will be generated during the course of this research, these types of bearings will be used for experimental purposes.

An investigation into rotor-bearing touchdown dynamics showed that an RDE can be characterised by various phases of motion. From most to least severe it is found that backward whirl, forward whirl, bouncing, oscillation and rolling of the rotor each differ in their destructive nature towards the BB system. These phases of motion will likely have to be individually considered when developing a method for predicting BB life. The AMB system available for this research has a relatively lightweight rotor, unknown rotor imbalance, rudimentary BB alignment method, rigidly mounted BB holders and very low to negligible damping on the BB system. Considering these system parameters, forward whirl is expected because the rotor was manufactured through basic machining and no balancing of the rotor has been done. Depending on the BB failure mode, large increases in bearing friction might occur which could induce destructive backward whirl of the rotor. Provisions will have to be made to ensure that rotor vibrations are contained to the BB system once bearing failure occurs.

In Section 2.4 various factors affecting BB life are investigated. The factors most likely to affect BB life for the available experimental setup are the rated speed of the bearing, the delevitation speed of the rotor, and the type of rotor motion during delevitation.

In Section 2.5 various bearing damage types were investigated. Due to the nature of delevitation events, many of the damage types found in standard bearing operation are expected to occur at a highly accelerated rate. BB failure can be very vendor specific and no specific information or definition regarding BB failure could be found. A BB failure analysis will be required to serve as a formal definition of BB failure for the AMB system used throughout this research. This definition will comply with the API specifications of being “*a consumable machinery protective device*” and ensure that rotor vibrations are contained to the BB assembly.

In Section 2.6 it is found that even though the API standard [39] has specific requirements regarding BB life, few literature sources focusing on BB degradation, preventative maintenance, BB life prediction and condition monitoring are available. Standard bearing life prediction methods do not apply since BBs are subjected to various highly non-linear operating conditions. The methods that directly apply to BB systems are highly simulation-based and rely on the knowledge of various system specific parameters. Implementation of these methods on commissioned AMB systems is unsatisfactory due to the need of predetermined and assumed initial conditions. Condition monitoring capabilities of these methods are also limited. The only method yielding true potential for predictive maintenance capabilities is based on monitoring shaft-delevitation position data and BB clearances after an RDE. The method described in [6] and [12] is based purely on shaft-delevitation data and yields potential for life prediction capabilities.

To investigate the usability of delevitation severity indicators for predicting BB life, bearing degradation data is required.

Chapter 3

Experimental method

This chapter contains information on the experimental setup used for gathering BB degradation data. Information regarding assumptions, experimental decisions, and the method followed for gathering BB degradation are shown. Experimental delevitation results are also shown and discussed.

3.1 Introduction

The focus of the proposed research is to investigate the usefulness of delevitation severity indicators for quantifying BB degradation. These indicators will be used to develop a method for predicting BB life based on repeated rotor delevitations. The secondary objective of this research is to obtain suitable BB degradation data using an experimental setup. The proposed research will be conducted in two phases to accomplish above-mentioned objectives. The two phases are respectively discussed in Chapter 3 and Chapter 4 and are as follow.

- Experimental BB failure analysis and degradation data acquisition
- Delevitation quantification using delevitation severity indicators

The first phase entails gathering BB degradation data using an experimental AMB system. BB failure modes and failure distributions will also be investigated. The method used to gather the above mentioned degradation data forms the main body of this chapter. The second phase of research investigates degradation quantification using the delevitation results obtained in phase one. Delevitation severity indicators will be used to quantify, evaluate and compare each delevitation to infer changes in BB performance characteristics. The changes in BB performance characteristics will then be used to investigate the usability of delevitation severity indicators for BB life prediction. Starting with the experimental setup, an investigation into phase one follows in the remainder of this chapter.

3.2 Experimental setup

The following section contains information on the active magnetic bearing, rotor, and BB system used to gather BB degradation data.

3.2.1 Active magnetic bearing system specification

Figure 3-1 shows the small-scale active magnetic bearing system used to induce the necessary delevitation conditions for gathering BB degradation data. The rotor is radially suspended by AMBs and axially suspended by a passive magnetic bearing system. Each AMB utilizes two eddy current inductive probes for measuring the vertical and horizontal displacement of the rotor within the AMB clearance. The system is modular allowing different types of rotors and BBs to be tested.

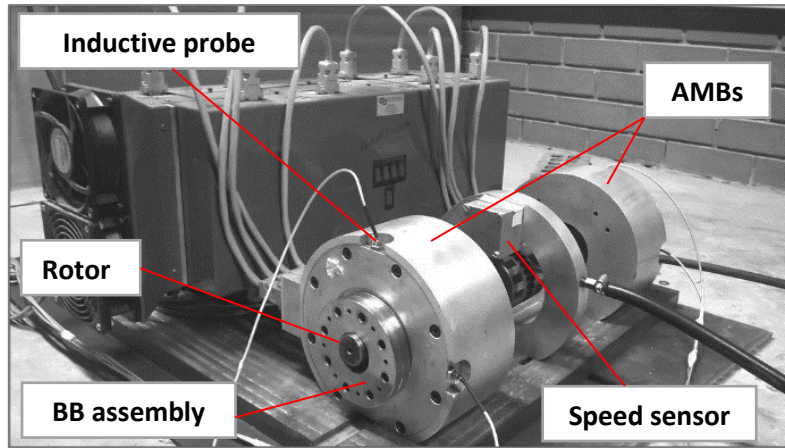


Figure 3-1: Small-scale experimental test bench used for rotor delevitation

3.2.2 Rotor specification

Figure 3-2 shows the rotor used during the course of this research. The rotor has a weight of 7.72 kg with a maximum operating speed of 30 000 r/min. The rotor is spun up to the desired operating speed using compressed air blowing onto a terry-turbine. By using compressed air, losses are minimized to air braking and BB friction once the AMBs and air propulsion units are shut down. The rotor speed is measured using an infrared optical speed sensor. For the purpose of this study, rotor delevitation speeds will be limited to a maximum of 8000 r/min due to the type of BBs used. A detail sketch of the rotor is shown in Appendix C.



Figure 3-2: Rotor used for experimental delevitation

3.2.3 Backup bearing specification

The BBs and bearing holders are rigidly supported with no added damping or compliant mounts. The lack of damping support is to minimize variables associated with compliant mount degradation. A single BB holder is mounted on each AMB to support the shaft radially when the rotor is not suspended. Deep groove ball bearings (6806) with a bore diameter of 30 mm are used as BBs. The rotor landing sleeves have an outer diameter of 29.6 mm, which leaves an airgap radius of 200 μm between the BB inner-race and rotor. For the purposes of this study, all bearing lubrication is removed from the BBs by placing them in a heated ultrasonic acetone bath. Lubricant-free bearings

are used to minimize variables associated with thermal effects on lubrication viscosity. The rotor is axially supported using a passive magnetic bearing system mounted on each AMB. Figure 3-3 shows a simplified sketch of the BB system assembly.

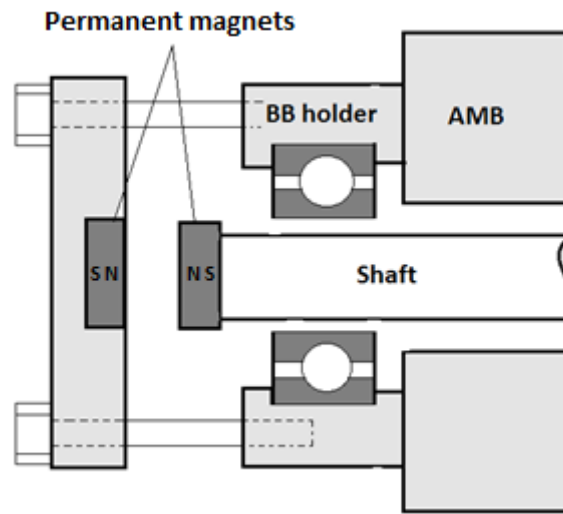


Figure 3-3: Diagram of the backup bearing system assembly

3.3 Delevitation severity indicators

In contrast to existing methods relying on force measurement capabilities, the quantification methods described within this section are purely based on shaft delevitation position and rotor speed data. This dependency on basic AMB sensor data enables the implementation of delevitation severity indicators on most, if not all, commissioned AMB units. The quantification methods include the overall non-dimensionalised distance travelled by the geometric centre of the rotor (*DVAL*) [12], the average non-dimensionalised velocity of the rotor (*VVAL*) [12], and the average non-dimensionalised deceleration of rotor (*AVVAL*) [49].

3.3.1 *DVAL*

To measure the severity of an RDE, the overall non-dimensionalised distance travelled by the geometric centre of the rotor (*DVAL*) is calculated. The distance travelled is non-dimensionalised by dividing it with the airgap radius and represents the number of times the rotor traversed the entire airgap distance. The non-dimensionalised distance travelled (*DVAL*) is given by the equation

$$DVAL(k) = \sum_i^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap}} \quad (3.1)$$

where i is the index number of a time-sampled data point, k the index number up to when the severity of the RDE is calculated, x and y the distance from the geometric centre of the BB in the x - and y -direction respectively, and r_{airgap} the clearance between the rotor and the BB inner-race.

Figure 3-4 presents a visual explanation of a single *DVAL* calculation based on an experimental RDE performed during this study.

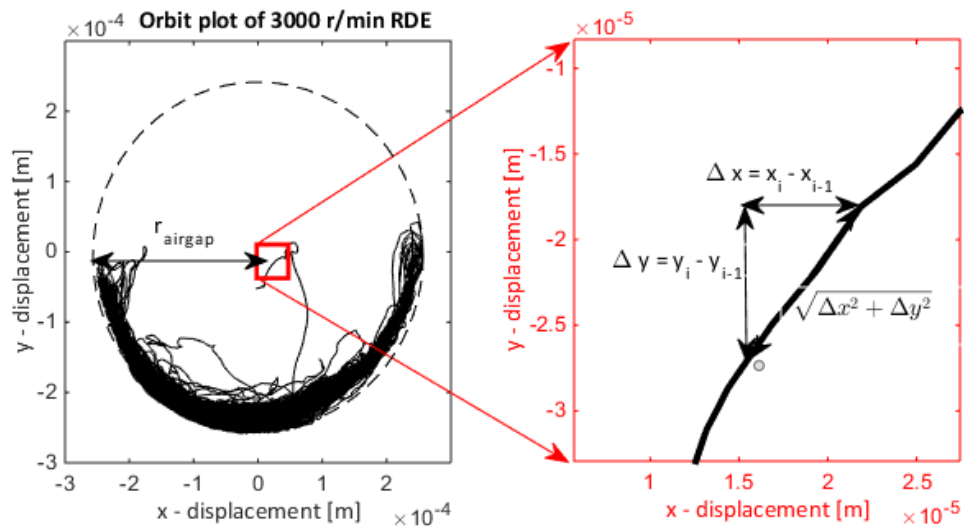


Figure 3-4: Graphical interpretation of the non dimensionalised distance (*DVAL*)

Figure 3-5 (left) shows the calculated values of *DVAL* against time for an RDE that occurred at 3000 r/min. It should be clear that the *DVAL* values of Figure 7 (left) result in quantification of the rotor's behaviour during the short time following an RDE. If the sampling frequency of the AMB system is 10 000 Hz, 1 second of delevitation time yields 10 000 iterations over which *DVAL* is calculated. Figure 3-5 (right) shows the calculated *DVAL* values plotted against its respective rotor speeds. The system's critical frequencies are found at the locations where a sudden change in gradient can be observed. The change in gradient indicates the frequencies at which increased or decreased amounts of transverse movement occur. A steeper gradient within the *DVAL* curve indicates a larger amount of transverse movement in a smaller amount of time.

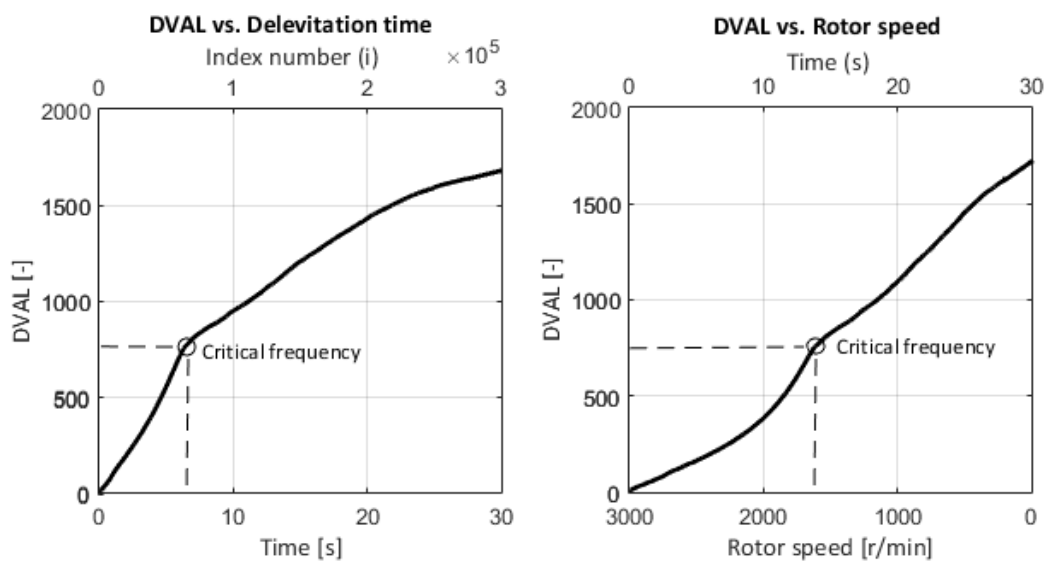


Figure 3-5: Example of a 3000 r/min RDE quantified using *DVAL*

3.3.2 VVAL

The second variable by which the severity of an RDE can be measured is the average non-dimensionalised velocity (*VVAL*), with a unit of s^{-1} . By calculating *VVAL*, an indication towards the amount of energy transformed into transverse movement can be determined. The reason for this is that translational velocity is an active variable in both equations of impulse and translational kinetic energy [11].

$$I \cong F \cdot \Delta t = m \cdot \Delta v \quad (3.2)$$

$$E_k = \frac{1}{2} \cdot m \cdot v^2 \quad (3.3)$$

The average non-dimensionalised velocity is given by the equation

$$VVAL(k) = \sum_i^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap} \cdot (t(i) - t)} \quad (3.4)$$

with $t(i)$ a time instant within a delevitation and t the time at the index number i . A higher *VVAL* value indicates larger amounts of transverse movement within a shorter amount of time.

3.3.3 AVVAL

The final variable for measuring the severity of an RDE is the average non-dimensionalised deceleration (*AVVAL*) with a unit of s^{-2} . By calculating *AVVAL*, an indication towards the amount of force transformed into transverse movement can be found. The reason for this is that acceleration is an active variable in the equation of average net force.

$$F = m \cdot a \quad (3.5)$$

The average non-dimensionalised deceleration is given by the equation

$$AVVAL(k) = \sum_i^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap} \cdot (t(i) - t)^2} \quad (3.6)$$

Similar to *VVAL*, a higher *AVVAL* value indicates a larger amount of transverse movement within a shorter amount of time.

3.4 Experimental procedure

This section discusses the method used to gather BB degradation data using the small-scale AMB system. Sufficient BB degradation data are required to investigate the usability of delevitation severity indicators for BB life prediction.

3.4.1 Degradation data acquisition process

BB degradation data are obtained by subjecting steel-caged rolling element bearings to repeated RDEs under numerous delevitation conditions. The delevitation tests are done by repeatedly levitating and spinning the rotor up to a speed that is 1000 r/min higher than that of the chosen delevitation speed. Once the speed is 1000 r/min higher than that of the chosen delevitation speed, the rotor is allowed to freely spin down and delevitate onto the BBs at a specific speed and angle from the geometric centre of the AMBs. The *DVAL* values for each delevitation are automatically calculated and logged once the RDE occurs. The delevitation process for a specific set of initial conditions is repeated until BB failure is evident. When failure occurs, the BBs are replaced and the process is repeated. Once a clear BB failure distribution and satisfactory degradation data at a specific initial condition are obtained, the initial conditions are changed. Figure 3-6 shows a flowchart of the BB degradation data acquisition process.

Repeatable bearing failures are required to have comparable degradation data for a specific set of initial conditions. At a specific initial condition, bearing failures with a standard deviation of 25% from the delevitation average until failure are deemed repeatable. The margin of error is chosen as such since BB failure is expected to occur randomly due to variations in bearing alignment, manufacturing tolerances and bearing cage quality.

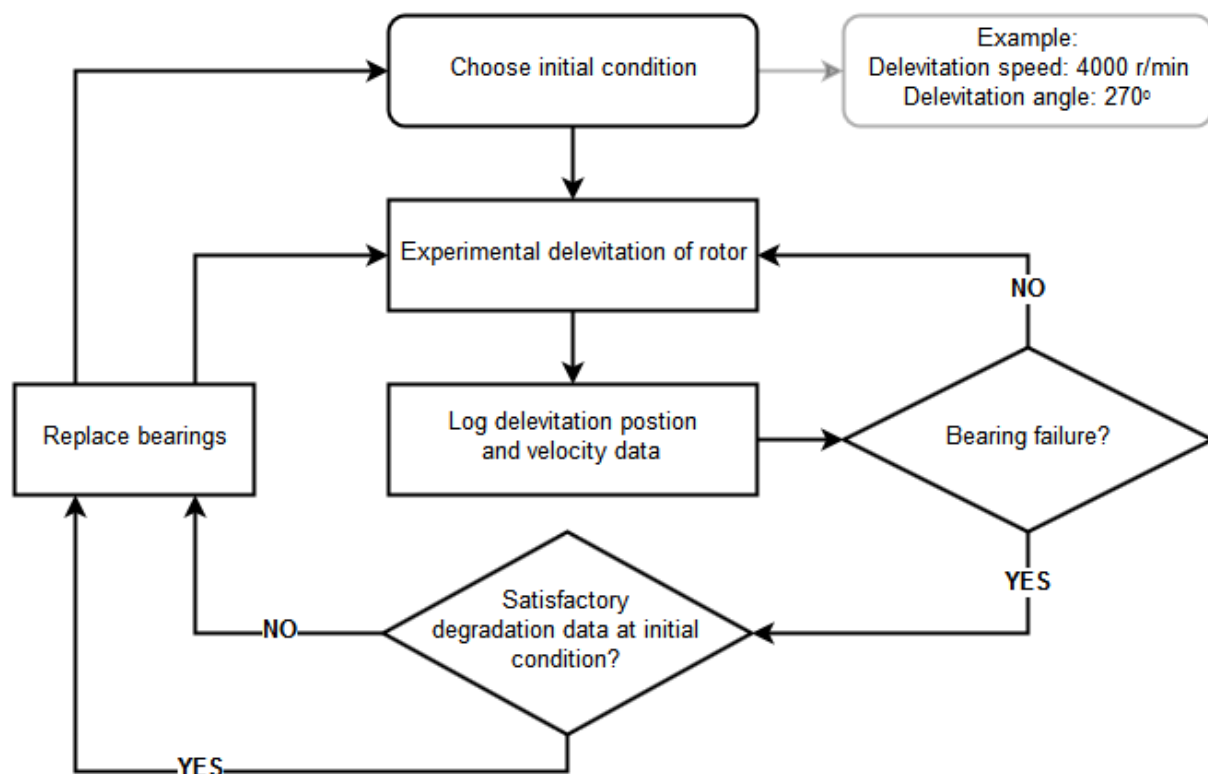


Figure 3-6: Bearing degradation data acquisition process

The following list shows the variables measured and recorded during each individual RDE:

- Left bearing x- and y-position of rotor
- Right bearing x- and y-position of rotor

- *DVAL* of left bearing as calculated in real time
- *DVAL* of right bearing as calculated in real time
- Delevitation duration
- Shaft rotational speed
- Number of delevitations until bearing failure

3.4.2 BB failure detection methods

Reitsma [10] suggests several main causes of BB failure. The main causes of BB failure can be one or a combination of corrosion, false brinelling, true brinelling, raceway spalling, fretting, misalignment, contamination, overheating and/or inadequate lubrication. The experimental delevitation results obtained within this chapter will be used to establish the cause of BB failure.

Reitsma [10] provides a few rudimentary methods that can be used to detect when BB failure had occurred. The methods include ball temperature monitoring, seismic vibration monitoring on the bearing outer ring, shaft rotational speed trending, RDE position trending, BB clearance checks and/or delevitated shaft hand roll checks. Due to the limited functionality of the experimental AMB system, only RDE position trending, hand roll checks and shaft rotational speed trending will be used to detect when BB failure had occurred. Additionally, visual inspection of the BBs within the bearing housing will be done to find traces of bearing damage. The API [39] indicates that rotor vibrations should be contained to the BB assembly and that the BBs should be “*a consumable machinery protective device*”. The satisfaction of these requirements will also be investigated.

3.5 Experimental results

This section discusses the experimental results obtained using the small-scale AMB system. Multiple bearing sets were subjected to various RDEs at different initial conditions. By inducing multiple RDEs at different initial conditions, the repeatability and characteristic nature of BB failure are investigated. A full discussion of the delevitation results follows in Section 3.6.

Table 3-1 shows a summary of ten separate sets of BBs exposed to four different initial conditions. The bearing sets shown were all subjected to multiple RDEs until noticeable signs of failure were observed. The RDE orbit plots for each bearing set can be found in Appendix B.

Table 3-1: Bearing failure results at various delevitation speed

	6000 r/min	5000 r/min	4500 r/min	4000 r/min
Bearing set	RDEs until failure	RDEs until failure	RDEs until failure	RDEs until failure
1	23	58	70	142
2	16	37	87	-
3	15	53	82	-
	Average: 18	Average: 49	Average: 80	Average: 142

Table 3-1 shows an average bearing failure deviation of 17% from the RDE average over all delevitation conditions. Figure 3-7 shows the bearing failure distribution for the results found in this table. This figure shows the number of RDEs until failure plotted against its respective delevitation condition.

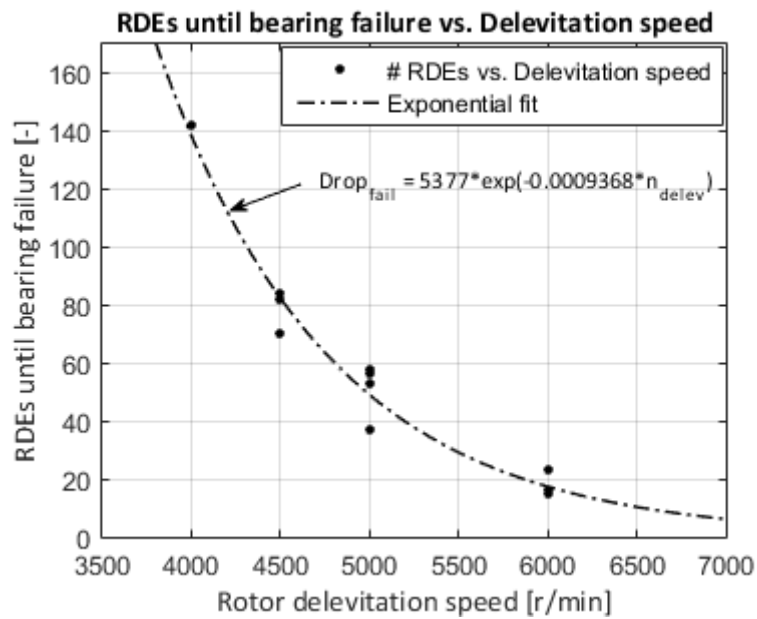


Figure 3-7: Bearing failure distribution curve

Closer inspection of Figure 3-7 yields a non-linear BB failure distribution. An exponential relationship between the number of RDEs until failure and the delevitation speeds exists. All of the failure detection methods discussed in Section 3.4.2 was able to detect when BB failure occurred. The methods, however, proved to be unusable since BB failure was only noticed once catastrophic failure of the bearing cage occurred. BB failure was always characterized by seizure of the rolling elements and severe backward whirl. No change in bearing condition and/or change in bearing performance characteristics between RDEs could be detected with the failure detection methods discussed. Figure 3-8 (Left) shows an example of the orbit plot trending used to study changes in rotor-bearing touchdown dynamics for a BB set exposed to numerous 4500 r/min RDEs until failure. Figure 3-8 (Right) shows the bearing at failure.

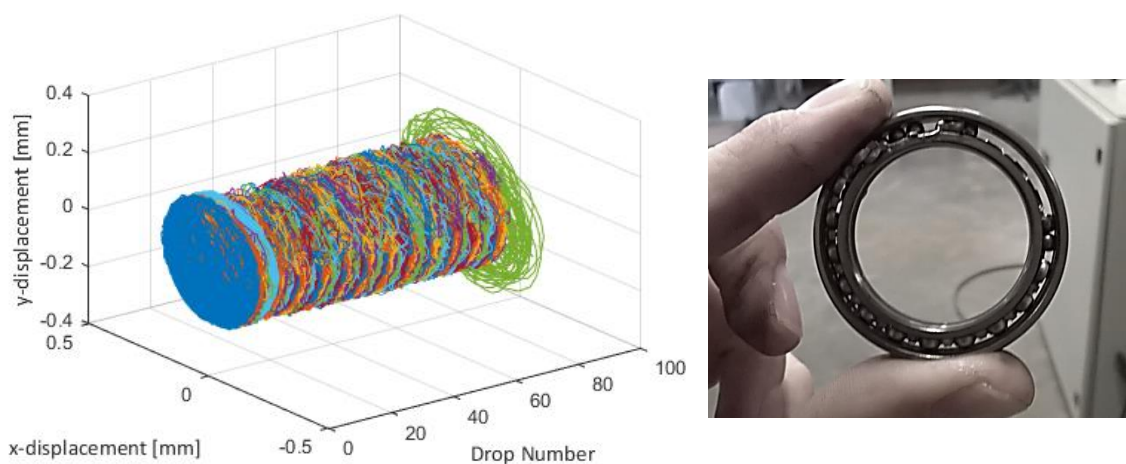


Figure 3-8: Illustration of catastrophic bearing cage failure caused by multiple RDEs

Similar results were found for all bearing sets shown in Table 3-1. The orbit plots for the respective bearing sets can be found in Appendix B. Figure 3-9 shows the orbit plot for multiple sets of BBs at failure. Not clear from this figure, catastrophic failure of the bearing components induced severe backward rotor whirl. Upon closer inspection of this figure, it can be observed that backward whirl caused the rotor to compress the bearing rolling elements with approximately 100 μm .

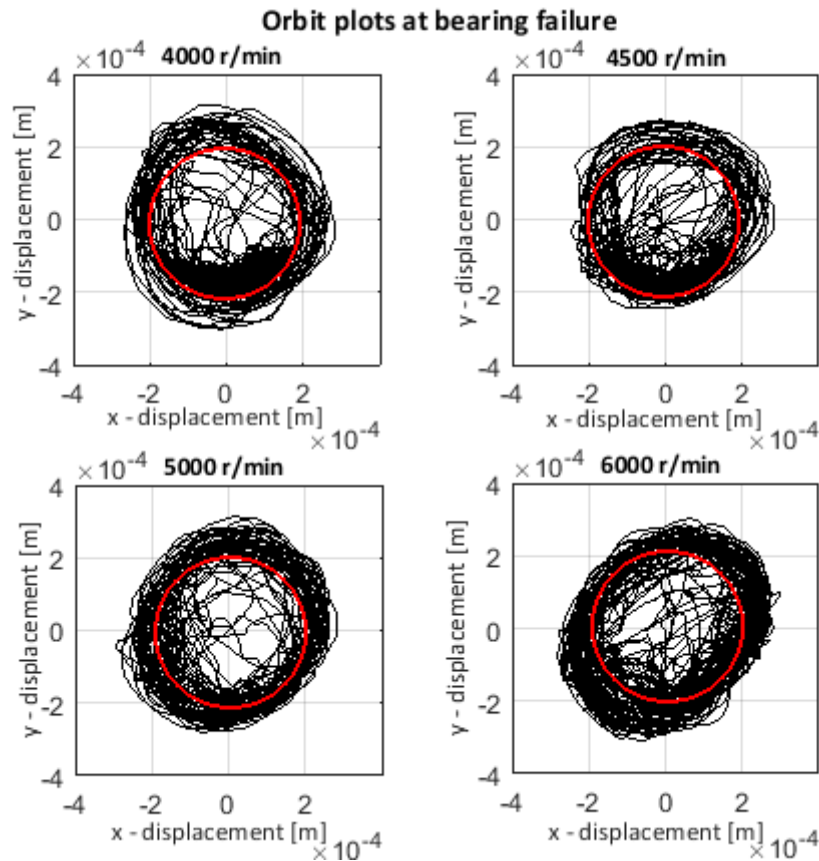


Figure 3-9: Illustration of rotor orbit plots at bearing failure

The following section contains a full discussion on the delevitation results

3.6 Discussion

Within this chapter a small-scale AMB system was used to generate BB degradation data by subjecting steel-caged rolling-element bearings to multiple RDEs. The RDEs were induced at specific initial conditions to analyse bearing failure distribution. Investigation into bearing failure distribution showed that different sets of bearings subjected to the same conditions failed at different stages of bearing life. BB failure only occurred at one bearing location at a time and alternated randomly between bearing locations. The random nature of the failure location is indicative of differences in bearing manufacturing quality and BB alignment.

All of the bearings contained fine metallic particles within the rolling elements. The metallic particles originated from wear on the bearing cage, balls and shaft landing sleeves. The wear might provide an explanation towards the cause of failure, where a gradual decrease in bearing cage quality ultimately resulted in failure of the bearing cage. Light traces of outer-race fretting were found at both bearing locations and provide indication of outer-race rotation within the bearing housing. The

light fretting most likely occurred upon failure of the bearing cage when the full rotational energy of the rotor was transferred from the bearing inner-race to the bearing outer-race. No indication of spalling, brinelling, or other damage types could visually be found.

Catastrophic failure of the bearing components induced severe backward whirling of the rotor and was mainly caused by increased rotor-bearing contact friction [32]. Backward whirl caused the rotor to compress the bearing rolling elements with approximately 100 μm . The rotor vibration for all delevitations was found to be contained to the BB assembly.

Figure 3-7 showed an exponential relationship between the RDEs until failure and the delevitation speed. As the delevitation speed of the rotor increases, the centripetal force of the rotor increases. The increased centripetal force of the rotor results in faster bearing spin up and possible skidding once rotor-bearing touchdown occurs [38]. The inconsistent bearing failure pattern can be attributed to varying bearing manufacturing tolerances, BB misalignment, inconsistent initial conditions, varying axial forces, and long-term rotor degradation.

Individually assessing the orbit plots for the Table 3-1 delevitations showed RDEs that entered a state of full forward whirl. No balancing of the rotor has previously been done. The forward whirl suggests that the rotor unbalance forces are larger than the static load [32]. All occurrences of full forward whirl only appeared above 3226 r/min. The occurrence of full forward whirl above this specific frequency suggests a reason to the exponential decay in BB life. An investigation into using delevitation severity indicators for analysing RDE severity and system critical frequencies will be required.

All of the failure detection methods discussed in Section 3.4.2 was able to detect when failure had occurred. The methods however produced undesirable results as bearing failure was only noticed once catastrophic failure of the bearing cage occurred. The failure always resulted in complete seizure of the bearing rolling elements that induced large-amplitude vibration and severe backward whirling of the rotor. Applying the failure detection methods between RDEs provided no indication of BB condition. An investigation into using delevitation severity indicators for degradation quantification and failure detection will be required.

Due to the non-linear BB failure pattern observed in Figure 3-7, the exponential fit equation will produce unsatisfactory BB life prediction and failure detection results. Use of the exponential fit equation could result in BB delevitation exposure even after possible low-severity failure occurred. The need for a life prediction method is justified when considering the high level of uncertainty associated with the BB's condition and violent rotordynamic motions. Both failure detection and life prediction capabilities will be deemed necessary.

To infer changes in BB performance over a series of RDEs, delevitation severity indicators are used to analyse each individual RDE. The investigation into using delevitation severity indicators for quantifying degradation will be discussed in the following chapter.

Chapter 4

Quantifying bearing degradation

This chapter contains information on the method used to quantify the BB degradation data obtained in Chapter 3. The usability of these delevitation severity indicators for life prediction and failure detection purposes are also investigated

4.1 Introduction

This chapter denotes the second phase of the proposed research. The first phase entailed gathering BB degradation data using an experimental AMB system. Subtle changes in bearing condition were found undetectable through physical investigation of the bearings and/or orbit plots. Changes in rotor-bearing touchdown dynamics might occur due to variations in BB condition. The second phase of the proposed research investigates degradation quantification using delevitation severity indicators. This investigation is based on the delevitation results obtained in phase one. Quantified bearing degradation data will be analysed for distinctive trends or threshold failure values usable for life prediction purposes.

Janse van Rensburg [12] recommended that further work should be done to determine how delevitation severity indicators can be used to quantify BB degradation. The severity indicators were primarily developed to verify simulation-based delevitation modelling techniques. The author does, however, indicate that delevitation severity indicators can be used to compare various RDEs to infer changes in rotor delevitation quality. It was also shown that a relationship between the amount of energy dissipated during an RDE and delevitation severity indicators exists. This relationship can then be used to rate rotor delevitation severity for condition monitoring purposes. Janse van Rensburg also states that delevitation severity indicators might be higher, or lower, depending on certain critical frequencies being traversed. Information regarding the use of these severity indicators to quantify degradation is lacking, most likely because they are relatively modern. An investigation into using delevitation severity indicators for quantifying degradation will be newly developed and covers the main topic of the research presented within this dissertation.

4.2 Degradation quantification method

Figure 4-1 shows a development flowchart for the degradation quantification and life prediction method. Bearing degradation data obtained in Chapter 3 will be quantified using delevitation severity indicators. The *DVAL*, *VVAL* and *AVVAL* values of each RDE for a specific set of BBs are calculated and compared to find changes in BB performance characteristics. If a clear change in the BB performance can be detected, a method for predicting BB life using the described delevitation severity indicators will be investigated. As stated previously, no specific information regarding the use of delevitation severity indicators for quantifying BB degradation is available. A method to quantify degradation and ultimately predict BB life will be newly developed.

Quantifying degradation for a series of full delevitations is firstly discussed. A full delevitation is initially used to investigate the occurrence of useful trends in quantified BB degradation data. If no distinctive trends usable for life prediction and failure detection purposes are found, bearing degradation will be quantified according to various rotordynamic motions. The rationale behind

calculating delevitation severity indicators according to various rotordynamic motions can be summarised as follow. The magnitudes of delevitation severity indicators are dependent on critical frequencies being traversed [12]. The transverse motion during an RDE is an indication of the energy dissipated by the BBs. The energy dissipated by the BBs during an RDE is an indication of the degradation of bearing quality [11]. Rotor rolling, oscillation, bouncing and whirling all differ in their degradative nature towards the BBs [12]. It might thus be imperative to calculate delevitation severity indicators according to different rotordynamic motions to find useful trends in quantified BB degradation data.

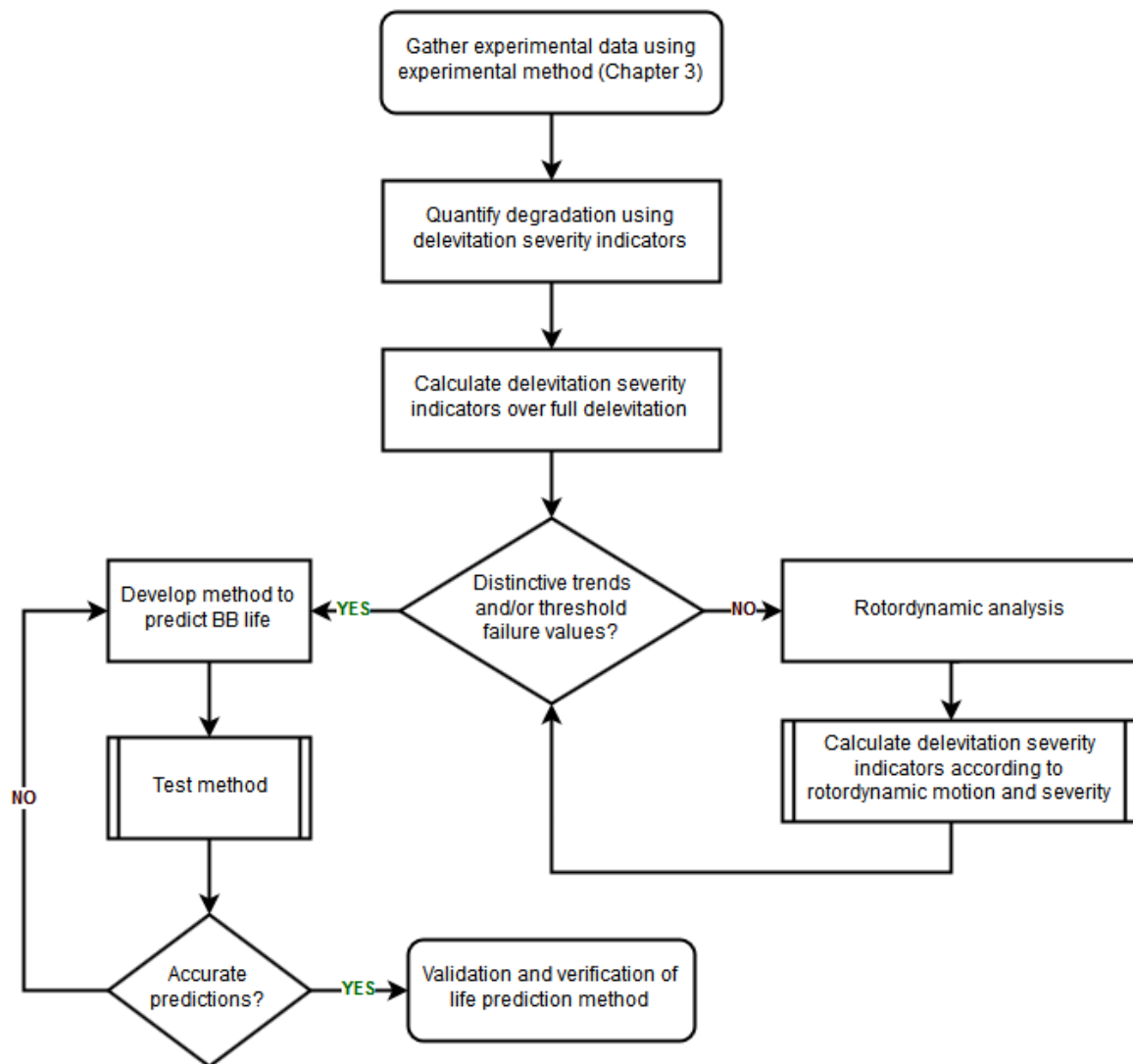


Figure 4-1: Flowchart of degradation quantification method

The following list shows the different investigations conducted to find a method for using delevitation severity indicators for life prediction and failure detection purposes:

- Quantifying degradation for a series of full delevitations
- Investigate the effect of various rotordynamic motions on delevitation severity indicators
- Quantifying degradation according to rotordynamic motion severity
- Identify the feasibility and use of delevitation severity indicators for life prediction and failure detection purposes.

4.3 Degradation quantification results

This section contains information on the results obtained from applying delevitation severity indicators to the bearing degradation data gathered in Chapter 3. The results are presented according to the method discussed in the previous section. The following section discusses degradation quantification for a series of full delevitations.

4.3.1 Quantifying degradation for a series of full delevitations

An example for calculating delevitation severity for a full delevitation is based on the first RDE of a bearing subjected to multiple 4000 r/min RDEs until failure occurred. To calculate delevitation severity according to the definition of *DVAL*, *VVAL* and *AVVAL*, equation (4.1) - (4.3) is used. The list below shows the variables recorded during the specified rotor speeds (4000 – 0 r/min).

- Index number at 4000 r/min, $i = 1$
- Index number at 0 r/min, $k = 876925$
- Time at index number i , $t = 0$ s
- Time at index number k , $t(i) = 87.6925$ s
- Airgap radius, $r_{airgap} = 200$ μm
- x - and y -position of rotor during delevitation can be found in appendix E

The non-dimensionalised distance travelled is given by

$$DVAL(k) = \sum_i^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap}} \quad (4.1)$$

$$DVAL(876935) = \sum_1^{876925} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{200 \times 10^{-6}}$$

$$= 10108$$

The non-dimensionalised average velocity is given by

$$VVAL(k) = \sum_i^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap} \cdot (t(i) - t)} \quad (4.2)$$

$$VVAL(876925) = \sum_1^{876925} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (87.6925 - 0)}$$

$$= 115.27 \text{ s}^{-1}$$

The non-dimensionalised average deceleration is given by

$$AVVAL(k) = \sum_i^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap} \cdot (t(i) - t)^2} \quad (4.3)$$

$$AVVAL(876925) = \sum_1^{876925} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (87.6925 - 0)^2}$$

$$= 1.3149 \text{ s}^{-2}$$

Figure 4-2 shows the calculated $DVAL(i)$, $VVAL(i)$ and $AVVAL(i)$ values plotted against rotor speed. The full calculation example can be found in Appendix A. It is important to note that Figure 4-2 only shows the first delevitation of a bearing subjected to numerous 4000 r/min RDEs. Similar results are found at both bearing locations due to complete AMB system symmetry. Consequently, only one bearing location is used for calculations.

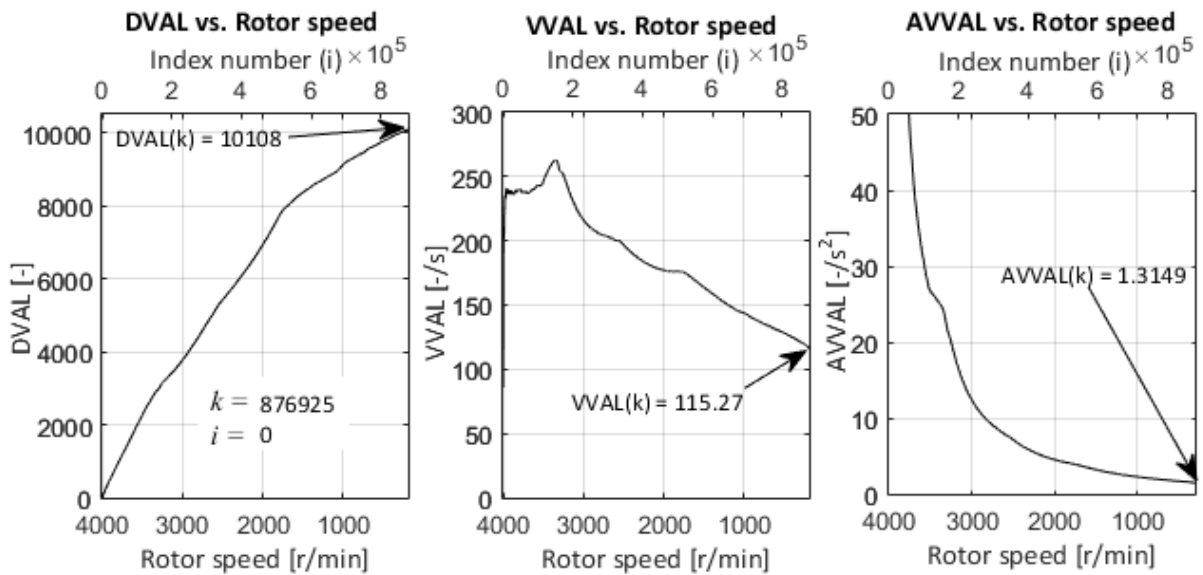


Figure 4-2: Severity of a single delevitation quantified using $DVAL$, $VVAL$ and $AVVAL$

The peak within the $VVAL$ plot of Figure 4-2 shows the rotor speed at which most severe transverse movement occurred. The large peak corresponds to the speed at which full forward whirl occurred. The smaller peaks within the plot indicate rotor speeds at which critical frequencies were traversed.

By quantifying the severity of a single RDE, the severity of subsequent RDEs can similarly be quantified and compared to infer changes in BB performance. Figure 4-3 shows the calculated delevitation severity indicator values for 142 successive RDEs until BB failure.

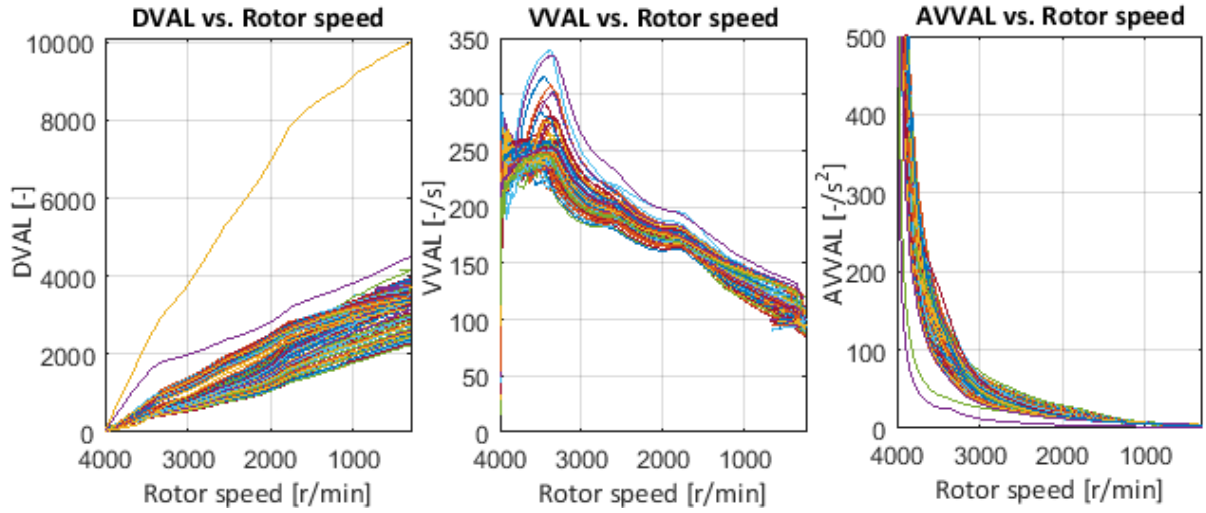


Figure 4-3: Severity of 142 delevitations quantified using *DVAL*, *VVAL* and *AVVAL*

From Figure 4-3 a definite change in BB performance characteristics over a series of RDEs can be observed. A clear trend is difficult to distinguish because of the significant number of RDEs shown. Regardless of the number of RDEs, experimental work during this study has shown that delevitation severity indicators do not seem to change if the BB condition remains the same. The shifting curves of Figure 4-3 suggest that changes in BB condition have occurred.

To highlight the change in BB performance over a series of RDEs, the severity indicator values at index number k are plotted against its RDE number. Figure 4-4 shows the calculated $DVAL(k)$, $VVAL(k)$ and $AVVAL(k)$ values of each RDE plotted against its RDE number.

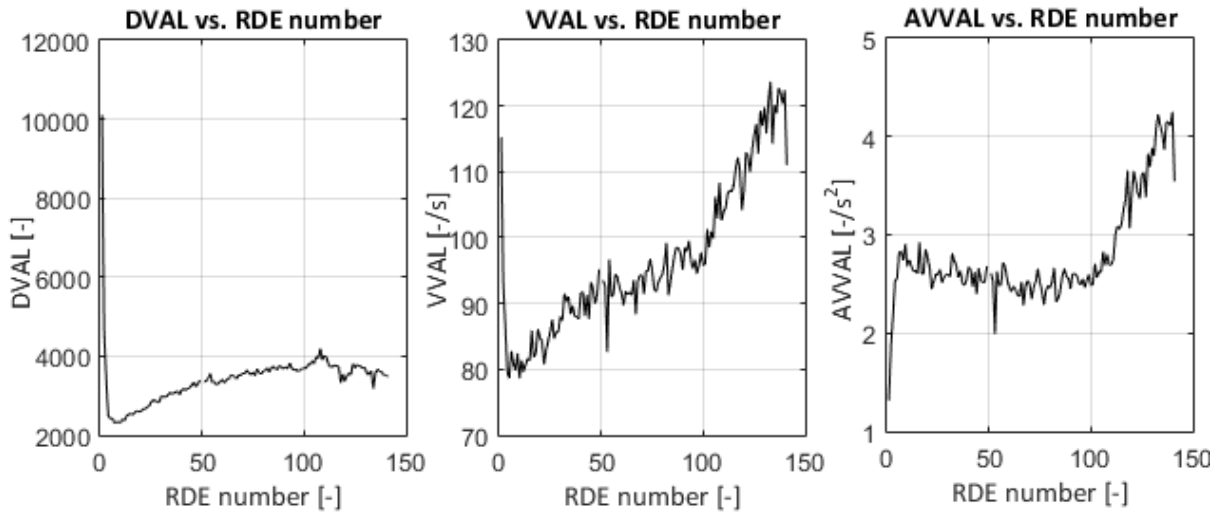


Figure 4-4: Degradation quantified using *DVAL*, *VVAL* and *AVVAL*

Closer inspection of Figure 4-4 reveals that the *DVAL* value increases as the RDE number increases. This increase only occurs up to RDE number 118 before a decrease occurs. The increasing *VVAL* value over a series of RDEs indicates that the amount of change in delevitation time is less than the amount of change in transverse movement between RDEs. The cause of the gradient change in *AVVAL* could be due to low-severity component failure within the BBs. The very high *DVAL* and very

low *AVVAL* values within the first few RDEs are caused by bearing run-in. The noise present between RDEs is mainly caused by inconsistencies in the initial conditions together with some position sensor noise.

Figure 4-5 shows similar results for the rotor delevitation tests found in Table 3-1. Each plot represents an individual set of BBs subjected to repeated RDEs until failure.

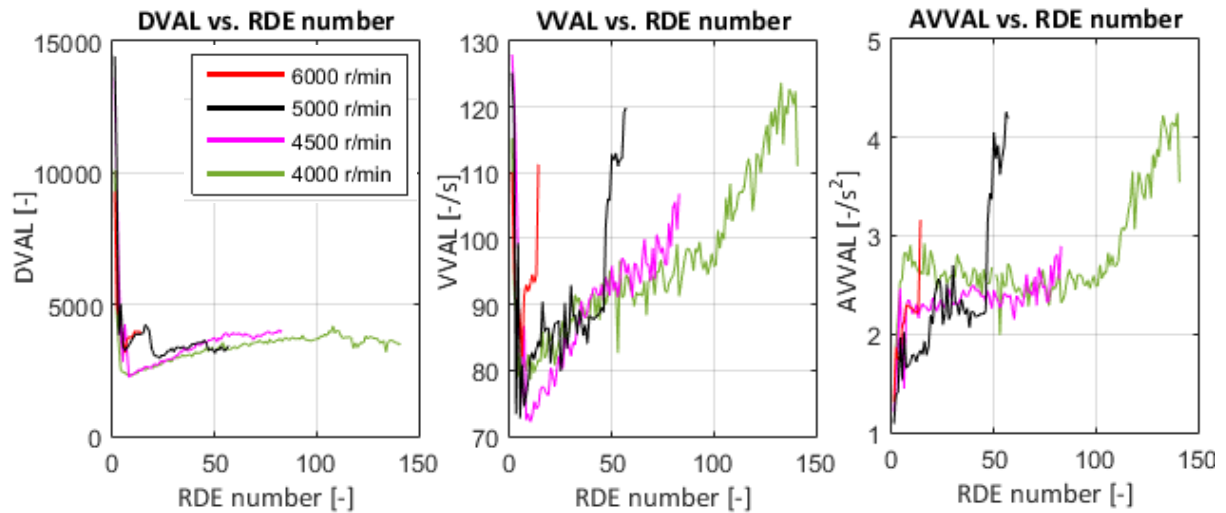


Figure 4-5: Degradation quantified for multiple delevitation conditions

Upon closer inspection of Figure 4-5, it is clear that by varying the delevitation speed, bearing degradation trends similar to that of Figure 4-4 are obtained. No distinct threshold failure values and/or trends usable for life prediction purposes are clear. Some unsatisfactory failure detection capabilities are possible at the locations where sudden spikes within the *VVAL* and *AVVAL* plots occur. Failure detection will be validated in Chapter 6.

The results from *VVAL* in Figure 4-3 showed that delevitation severity differs within various stages of rotor delevitation. A rotor can be subjected to various rotordynamic states during an RDE that can be either one or a combination of the following: rolling, oscillation, bouncing, forward whirl, or backward whirl [2]. The above-mentioned rotordynamic states differ in their destructive nature towards the BBs. Investigations into the influence of various rotordynamic motions on delevitation severity indicators will be done to increase degradation quantification sensitivity. To achieve this, a system critical frequency analysis will be conducted and discussed in the following section.

4.3.2 Rotordynamic analysis using delevitation severity indicators

In the previous section, delevitation severity indicators yielded unsatisfactory degradation quantification results when calculated for a full RDE.

To study the magnitude and types of transverse movement present during various stages of an RDE without the use of force measurement capabilities requires another approach. Not shown by Janse van Rensburg [12], differentiating *DVAL* with respect to time yields the number of times per second that the airgap distance is traversed ($\Delta DVAL$). This $\Delta DVAL$ yields an indication towards variations in rotor velocity and the frequencies at which rotor movement is most severe.

Figure 4-6 shows $\Delta DVAL$ plotted against rotor speed. The three delevitations were initiated at different rotor speeds whilst logging the $DVAL$ values. From this figure, three main rotordynamic states are identified. The rotordynamic states are labelled as cases A, B and C. Figure 4-7 shows the actual rotor movement during each of these states using orbit plots.

Closer inspection of Figure 4-6 and Figure 4-7 shows that the type and magnitude of rotor movement are independent of the delevitation speed. The most severe transverse movement occurs between 6000 and 2500 r/min. For all delevitations up to point 1, a combination of heavy bouncing and forward whirling occurs. Between point 1 and 2 a clear increase and sudden decrease in rotor movement occurs as the system whirling frequency is traversed. The large peaks present within the 4500 and 4000 r/min delevitations show the moment when full forward whirl occurred. The 6000 r/min delevitation failed to enter a state of full forward whirl, hence the absence of a large peak. Between point 2 and 3, a combination of light forward whirl and mostly oscillation occurs. Point 3 up to point 4 shows the moment when the rotor enters the first critical frequency and a state of almost pure oscillation. Even though the peak after point 3 seems similar to the one found between point 2 and 3, their respective motions differ considerably. The first peak contains a combination of light forward whirl and oscillation whilst the second peak exhibits no forward whirl. From point 4 up to where rotor standstill is reached, persistent contact with the BBs is mostly maintained because a rolling motion is induced.

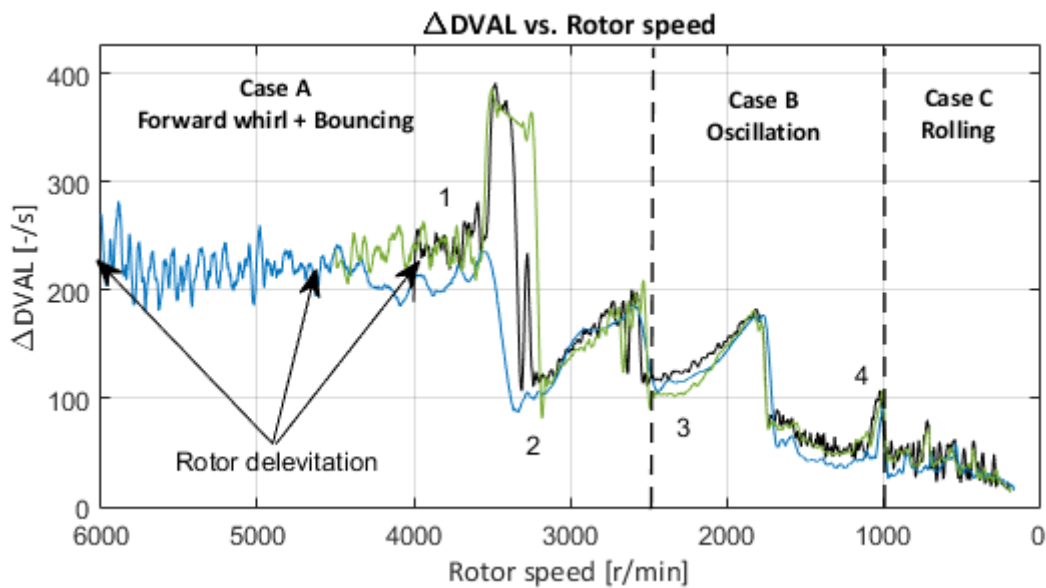


Figure 4-6: Severity of rotor motion within various stages of rotor delevitation ($\Delta DVAL$)

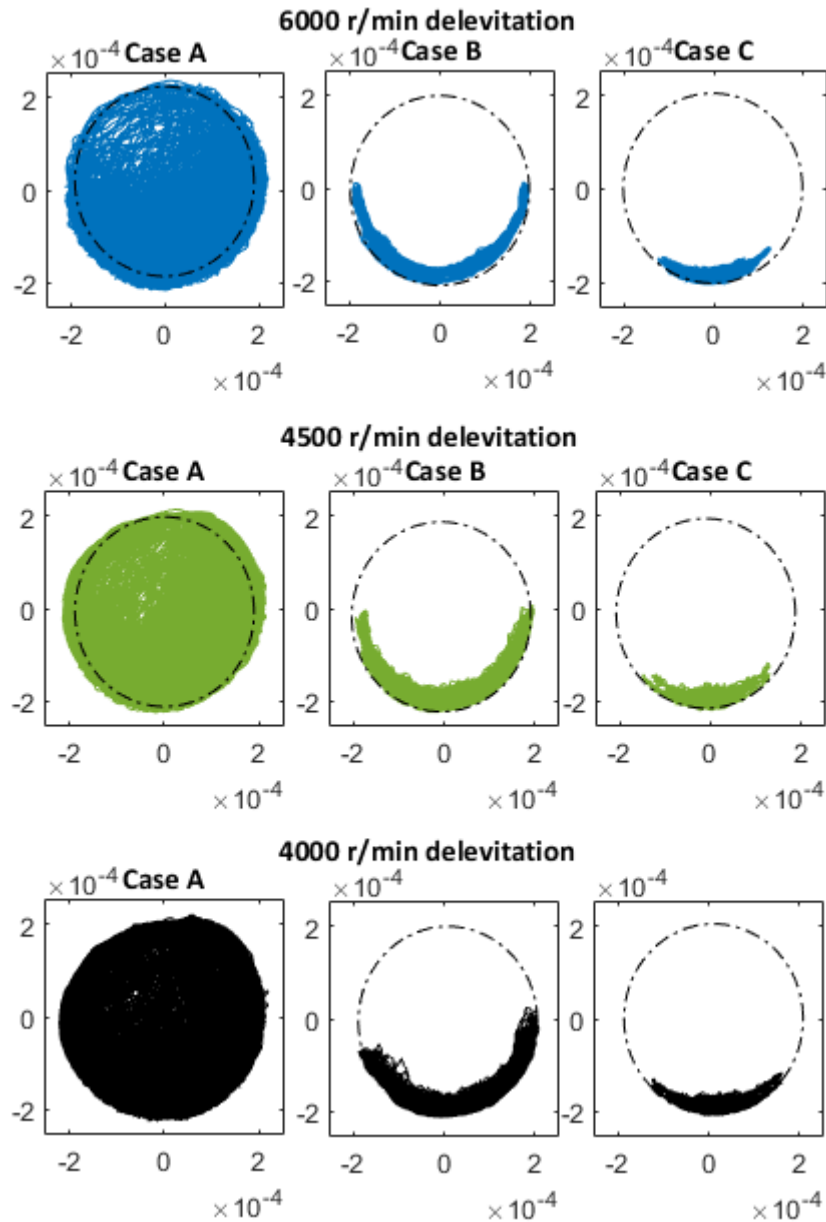


Figure 4-7: Illustration of rotor motion within various stages of rotor delevitation

Although Figure 4-6 provides some indication towards the severity of the different rotordynamic motions, the difference between the first and second critical frequency is unclear. To correctly identify and calculate delevitation severity indicators according to the most severe rotor movement, $\Delta DVAL$ is once again differentiated with respect to time. This $\Delta^2 DVAL$ provides an indication towards changes in rotor vibration and is shown in Figure 4-8.

Closer inspection of Figure 4-8 shows that the magnitude of rotor vibration differs considerably between the first and second critical frequency. As stated previously, the second critical frequency contains a combination of light rotor whirl, bouncing and oscillation whilst the first critical frequency only contains oscillation. To investigate the usability of delevitation severity indicators for life prediction and failure detection, delevitation severity indicators will be calculated according to the various rotordynamic cases presented.

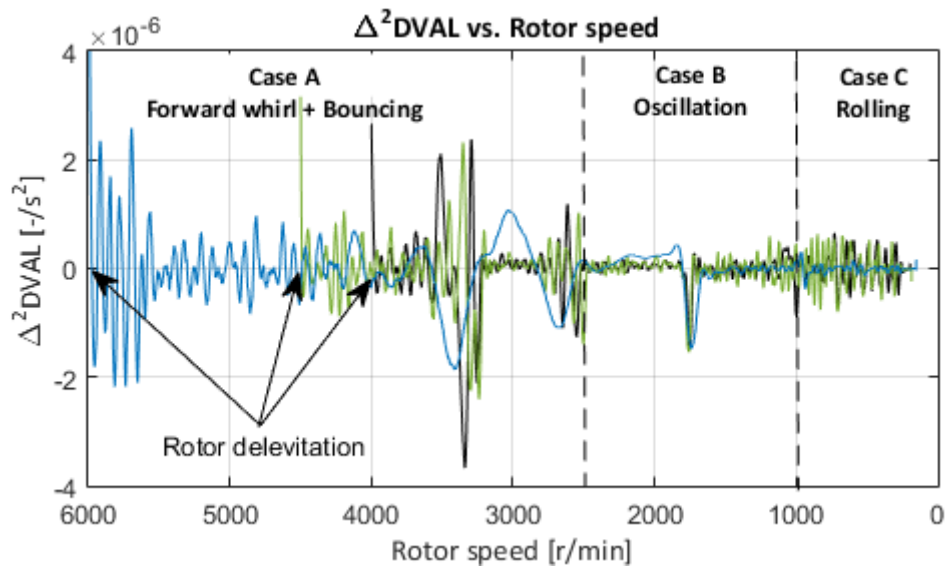


Figure 4-8: Vibration analysis using $\Delta^2 DVAL$

By calculating delevitation severity indicators during the period when rotor bounce and whirl occur, the effects of rotor rolling and oscillation on delevitation severity indicators are excluded (Case A). As obtained from Figure 4-7 and Figure 4-8, the speed at which the rotor enters rolling and oscillation is at 2500 r/min. For this case, delevitation severity will be calculated over the time period from rotor delevitation up to the time when the rotor reaches a speed of 2500 r/min. This rotor speed corresponds to the peak of the second critical frequency of the system (verified later in Chapter 6). The rotordynamic motions during this phase are deemed the most destructive towards the BBs. Calculating delevitation severity indicators over this phase are expected to yield some life prediction capabilities. Life prediction capabilities are expected because of the relationship between bearing degradation and the energy dissipated by the BBs during an RDE.

An investigation into Case B might prove useful in failure detection because of the system friction's dynamic nature and the associated influence on the delevitation time and transverse movement. By calculating delevitation severity indicators over this period (2500 – 1000 r/min), changes in delevitation time are expected to have a larger influence on the magnitude of delevitation severity indicators than changes in transverse movement between RDEs. This reduced influence of transverse movement on delevitation severity indicators is because of the presence of rotor sliding and rolling. Detection of sudden increases in bearing friction during this phase is expected.

An investigation into Case C might also prove useful in failure detection because of the system friction's dynamic nature and the associated influence on the delevitation time and transverse movement. By calculating delevitation severity indicators over the period when an almost pure rolling motion of the rotor is present (1000 – 0 r/min), a sudden variation in delevitation duration will greatly influence the magnitude of delevitation severity indicators. During a rolling motion, persistent contact and minimal sliding with the bearing inner-race will yield a small $DVAL$ value. Thus, calculation over this period will be less dependent on variations in transverse movement than sudden changes in delevitation time. Detecting large sudden variations in system friction might be possible during a rolling motion. An increase in bearing friction is expected to reduce the delevitation time.

To develop a method for life prediction and failure detection purposes using the described severity indicators, the following assumptions are made:

- If it is assumed that increased BB degradation is proportional to increased bearing friction, and increased friction is proportional to decreased delevitation time and transverse movement, then delevitation severity indicators yield an indication towards BB degradation. These relationships are assumed since the magnitude of delevitation severity indicators is dependent on both the time and the amount of transverse movement during an RDE.
- If it is assumed that some rotordynamic motions have minimal to negligible effects on overall bearing life, then the most violent rotordynamic motions will subject the BBs to a maximum cumulative amount of energy that the rolling elements can absorb before failure occurs.

An investigation into the individual cases found in Figure 4-6 will now be discussed

4.3.3 Quantify bearing degradation according to rotordynamic severity

In the previous section, various rotordynamic motions during an RDE were identified. The main rotordynamic motions were identified as one or a combination of rotor whirl, bouncing, oscillation and rolling. The following sections investigate degradation quantification during each of the above-mentioned rotordynamic motions.

4.3.3.1 Case A: Life analysis during forward whirling and bouncing (BB life prediction)

In Figure 4-7 and Figure 4-8, it was found that the most destructive rotordynamic motions occur above the peak of the second critical frequency (Rotor delevitation speed – 2500 r/min). An example for calculating delevitation severity according to the most severe rotordynamic motion is based on the first RDE of a bearing subjected to multiple 4000 r/min delevitations until failure occurred. The list below shows the variables recorded during the specified rotordynamic motion.

- Index number at 4000 r/min, $(i) = 1$
- Index number at 2500 r/min, $(k) = 275767$
- Time at index number i , $t = 0$ s
- Time at index number k , $t(i) = 27.5767$ s
- Airgap radius, $(r_{airgap}) = 200$ μm
- x - and y -position of rotor during delevitation can be found in appendix E

The non-dimensionalised distance travelled is given by

$$DVAL(275767) = \sum_1^{275767} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{200 \times 10^{-6}} \quad (4.4)$$

$$= 5418.9$$

The non-dimensionalised average velocity is given by

$$VVAL(275767) = \sum_1^{275767} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (27.5767 - 0)} \quad (4.5)$$

$$= 196.69 \text{ s}^{-1}$$

The non-dimensionalised average deceleration is given by

$$AVVAL(275767) = \sum_{i=1}^{275767} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (27.5767 - 0)^2} \quad (4.6)$$

$$= 7.1396 \text{ s}^{-2}$$

The full calculation example can be found in Appendix A. Figure 4-9 shows the calculated $DVAL(i)$, $VVAL(i)$ and $AVVAL(i)$ values plotted against rotor speed from the instant of delevitation up to 2500 r/min. This figure only shows the first RDE of a bearing subjected to numerous 4000 r/min RDEs.

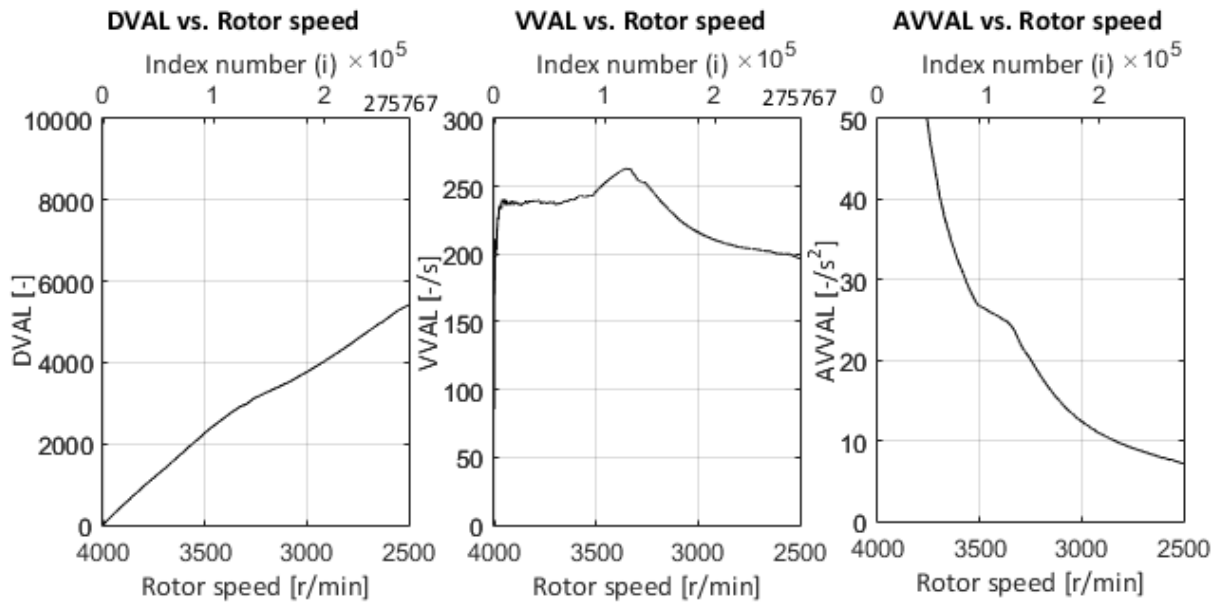


Figure 4-9: Severity of a single delevitation quantified during a whirl and bouncing motion

By quantifying the severity of a single RDE, the severity of subsequent RDEs can be quantified and compared to infer changes in BB performance. Figure 4-10 shows the calculated delevitation severity indicator values for 142 successive RDEs conducted on a bearing until failure occurred.

From Figure 4-10 a definite change in BB performance characteristics over a series of RDEs can be observed. A clear trend however is difficult to distinguish because of the significant number of RDEs shown. Regardless of the number of RDEs that have occurred, experimental work during this study has shown that the delevitation severity indicators do not seem to change if the BB condition remains the same. The shifting curves of Figure 4-10 suggest that changes in BB performance characteristics have occurred.

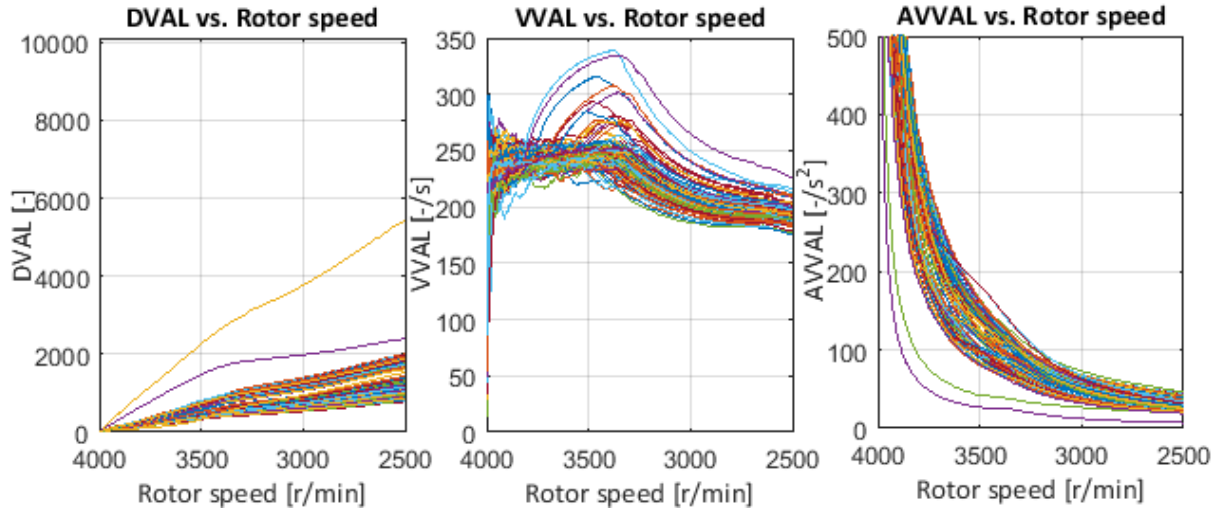


Figure 4-10: Severity of 142 delevitations quantified during a whirl and bouncing motion

To highlight the change in BB performance observed in Figure 4-10, the severity indicator values calculated at the index number k are plotted against their respective RDE number. Figure 4-11 shows $DVAL(k)$, $VVAL(k)$ and $AVVAL(k)$ of each RDE plotted against its RDE number.

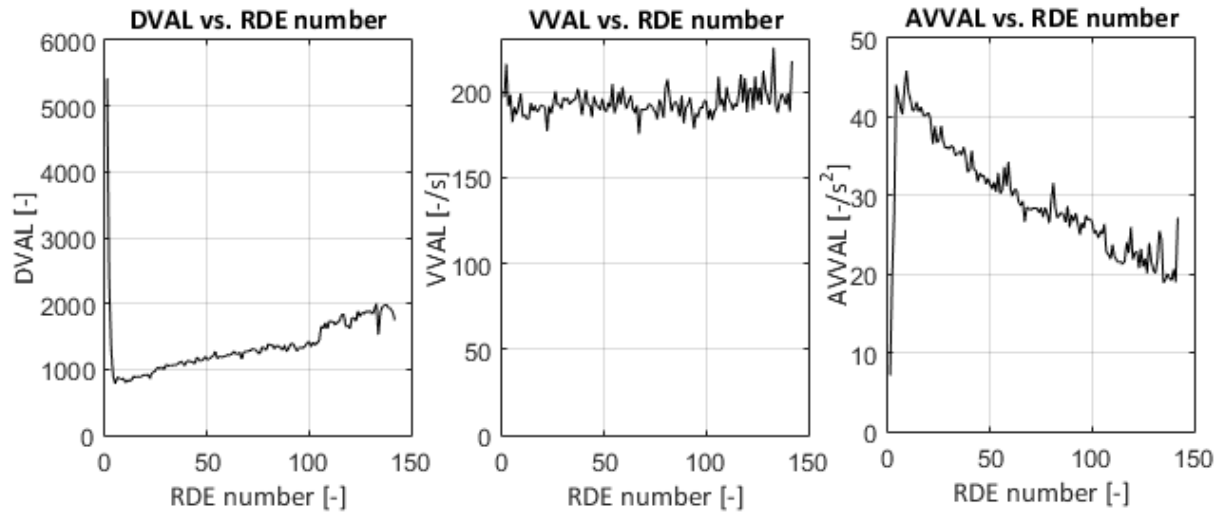


Figure 4-11: Degradation quantified during a bouncing and whirl motion

In comparison to Figure 4-10, Figure 4-11 provides a clear indication of the performance changes within the BB system. The maximum $DVAL$ value increases as the RDE number increases whereas the $AVVAL$ value decreases as the RDE number increases. The $VVAL$ value does not yield any clear indication of changes in BB performance but does indicate that the change in transverse movement is equal to the change in time between delevitations. The equal change in time and transverse movement might explain the decreasing $AVVAL$ value. If the change in transverse movement between RDEs is equal to the change in delevitation time, any change in delevitation time will have a non-linear influence on the magnitude of $AVVAL$. Since no clear changes in BB performance can be seen from $VVAL$, only $DVAL$ and $AVVAL$ will be considered in the remainder of this section.

Figure 4-12 shows the calculated *DVAL* and *AVVAL* values for the RDE tests found in Table 3-1. Each plot represents an individual set of BBs subjected to repeated delevitations until failure occurred.

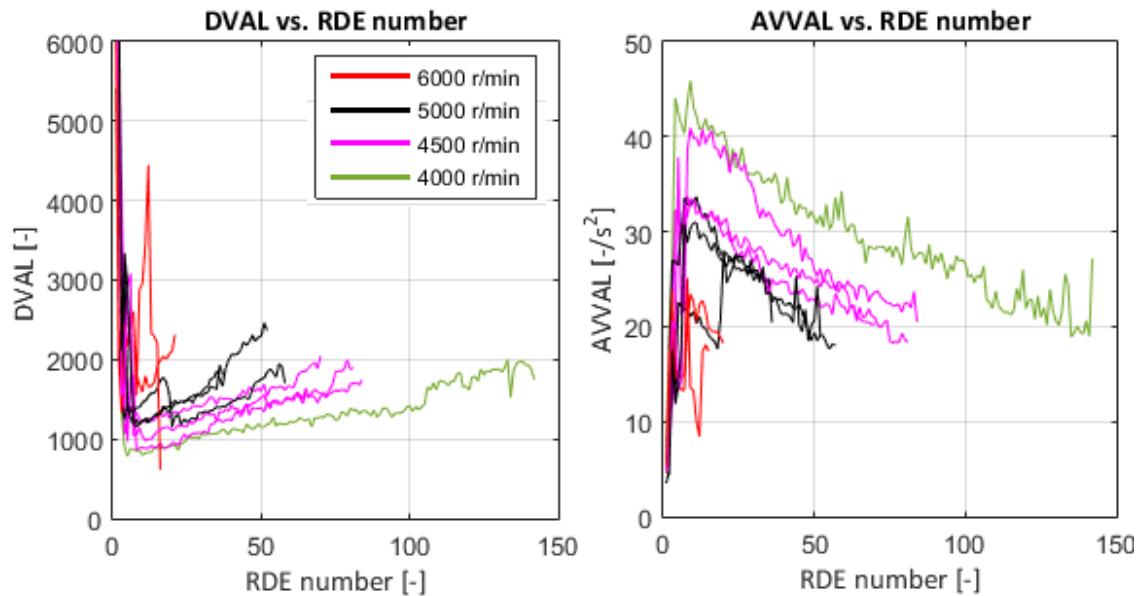


Figure 4-12: Degradation quantified during a bouncing and whirl motion for multiple conditions

Closer inspection of Figure 4-12 reveals linear degradation patterns for all bearing sets shown. Further investigation of this figure also reveals that bearing failure, independent of the delevitation speed, occurs once a *DVAL* value of approximately 2000 and an *AVVAL* value of approximately 20 are reached. The distinct linear degradation pattern and identified threshold value yield potential for BB life prediction purposes. BB life prediction using the linear degradation pattern and failure threshold values will be discussed in Chapter 5. Investigation into Case B as found in Figure 4-7 and Figure 4-8 will now be discussed.

4.3.3.2 Case B: Life analysis during oscillating motion

For case B, life analysis is done during the period when an oscillating motion is present (2500 – 1000 r/min). This example is based on the first RDE of a bearing subjected to 142 RDEs until failure. The list below shows the variables recorded during the specified rotordynamic motion.

- Index number at 2500 r/min, $i = 275767$
- Index number at 1000 r/min, $k = 636278$
- Time at index number i , $t = 27.5767$ s
- Time at index number k , $t(i) = 63.6278$ s
- Airgap radius, $(r_{airgap}) = 200$ μm
- x - and y -position of rotor during delevitation can be found in appendix E

The non-dimensionalised distance travelled by the geometric centre of the rotor is given by

$$DVAL(636278) = \sum_{275767}^{636278} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{200 \times 10^{-6}} \quad (4.7)$$

$$= 3718.3$$

The non-dimensionalised average velocity is given by

$$VVAL(636278) = \sum_{275767}^{636278} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (63.6278 - 27.5767)} \quad (4.8)$$

$$= 103.2404 \text{ s}^{-1}$$

The non-dimensionalised average deceleration is given by

$$AVVAL(636278) = \sum_{275767}^{636278} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (63.6278 - 27.5767)^2} \quad (4.9)$$

$$= 2.8665 \text{ s}^{-2}$$

The full calculation example can be found in Appendix A. Figure 4-13 shows the calculated $DVAL(i)$, $VVAL(i)$ and $AVVAL(i)$ values plotted against rotor speed during an oscillating motion. This figure only shows the first RDE of a bearing subjected to numerous 4000 r/min RDEs.

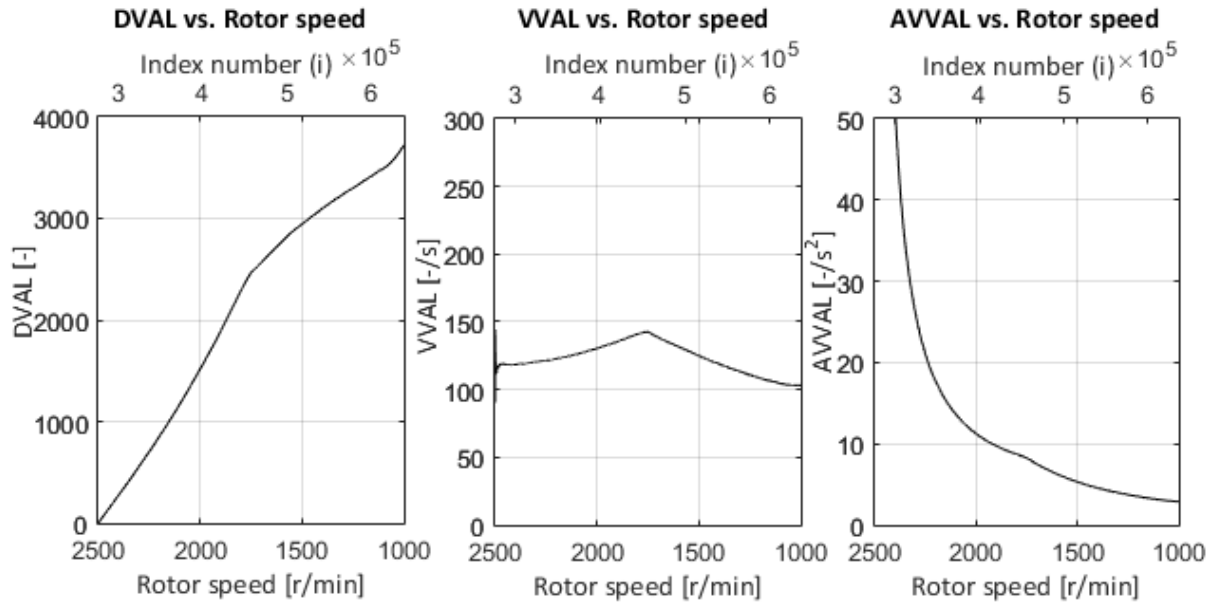


Figure 4-13: Severity of a single delevitation quantified during an oscillating motion

Figure 4-14 shows the severity of 142 successive delevitations at 4000 r/min quantified over the period when an oscillating motion occurs.

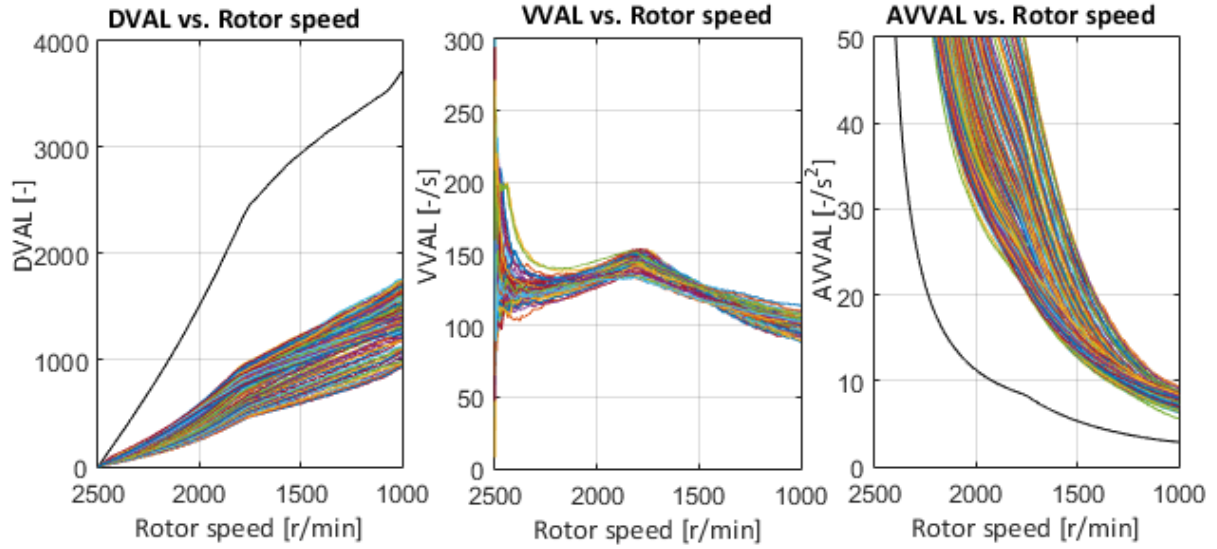


Figure 4-14: Severity of 142 delevitations quantified during an oscillating motion

To highlight the change in BB performance over a series of RDEs, the severity indicator values calculated at index number k are plotted against its RDE number. Figure 4-15 shows $DVAL(k)$, $VVAL(k)$ and $AVVAL(k)$ of each RDE plotted against its RDE number.

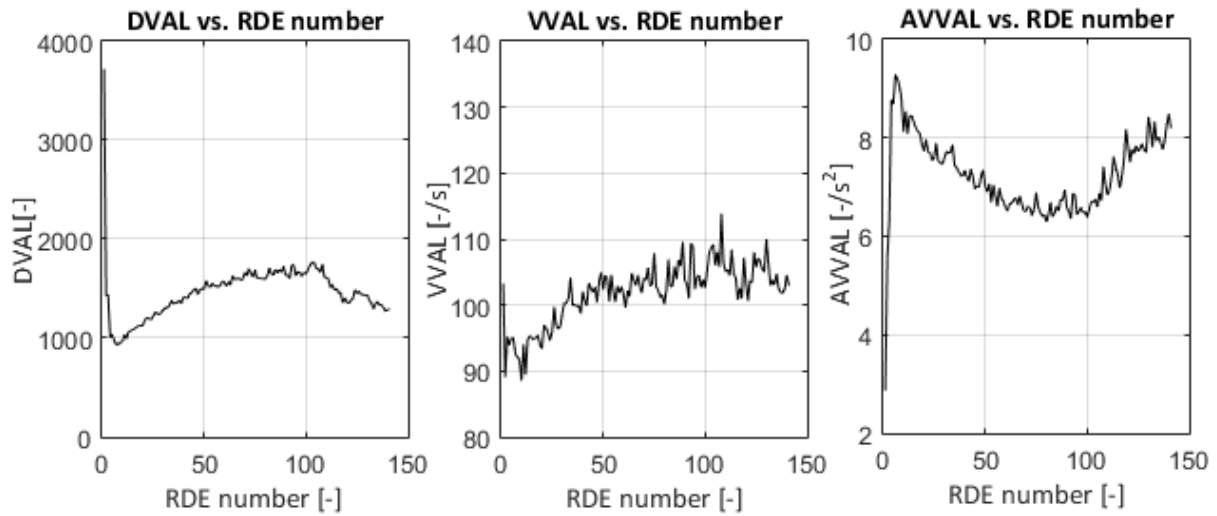


Figure 4-15: Degradation quantified during an oscillating motion

Figure 4-16 shows the calculated $DVAL(k)$ and $AVVAL(k)$ values for the RDEs found in Table 3-1. Each plot represents an individual set of BBs subjected to numerous repeated delevitations until failure occurred. Only $DVAL$ and $AVVAL$ will be considered in the remainder of this section since it produced the most significant trends.

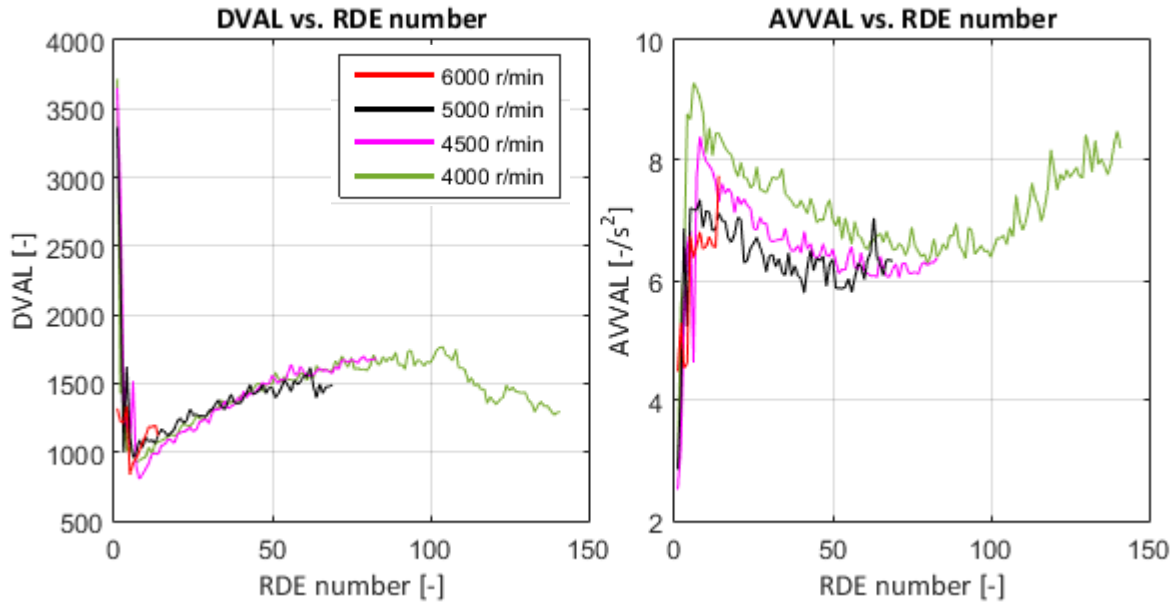


Figure 4-16: Degradation quantified during an oscillating motion for multiple conditions

From Figure 4-16, it is determined that *DVAL* and *AVVAL* produces similar results to that of Case A. A threshold value when bearing failure occurs is also evident although not as definite as for a bouncing/whirling motion. The plots additionally provide possible information on the RDE number where low-severity bearing failure occurred. Low-severity BB failure is characterised by the RDE number where the linear degradation pattern changes from a negative to positive gradient. The negative gradient indicates an increase in delevitation time caused by a gradual decrease in rolling friction. The positive gradient indicates a sudden decrease in delevitation time as rolling friction suddenly increases. During an oscillating motion, persistent contact between the rotor and bearing inner-race is not always maintained and an indication towards increased rolling friction is not as clear as it would be during a rolling motion. An investigation into a rolling motion (Case C) will now be discussed.

4.3.3.3 Case C: Life analysis during rolling motion (BB Failure detection)

For Case C, life analysis is done during the period when a rolling motion is present (1000 – 0 r/min). This example is based on the first RDE of a bearing subjected to multiple 4000 r/min RDEs until failure. The list below shows the variables recorded during the specified rotordynamic motion.

- Index number at 1000 r/min, $i = 636278$
- Index number at 0 r/min, $k = 876925$
- Time at index number i , $t = 63.6278$ s
- Time at index number k , $t(i) = 87.6925$ s
- Airgap radius, $(r_{airgap}) = 200$ μm
- x - and y -position of rotor during delevitation can be found in appendix E

The non-dimensionalised distance travelled by the geometric centre of the rotor is given by

$$DVAL(876925) = \sum_{636278}^{876925} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{200 \times 10^{-6}} \quad (4.10)$$

$$= 954.7$$

The non-dimensionalised average velocity is given by

$$VVAL(876925) = \sum_{636278}^{876925} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (87.6925 - 63.6278)} \quad (4.11)$$

$$= 40.83 \text{ s}^{-1}$$

The non-dimensionalised average deceleration is given by

$$AVVAL(876925) = \sum_{636278}^{876925} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (87.6925 - 63.6278)^2} \quad (4.12)$$

$$= 1.746 \text{ s}^{-2}$$

Figure 4-17 shows the $DVAL(k)$, $VVAL(k)$ and $AVVAL(k)$ values of 142 successive delevitations at 4000 r/min quantified over the period when an oscillating motion occurs. The delevitation severity indicator values obtained from equation (4.10) - (4.12) are also highlighted.

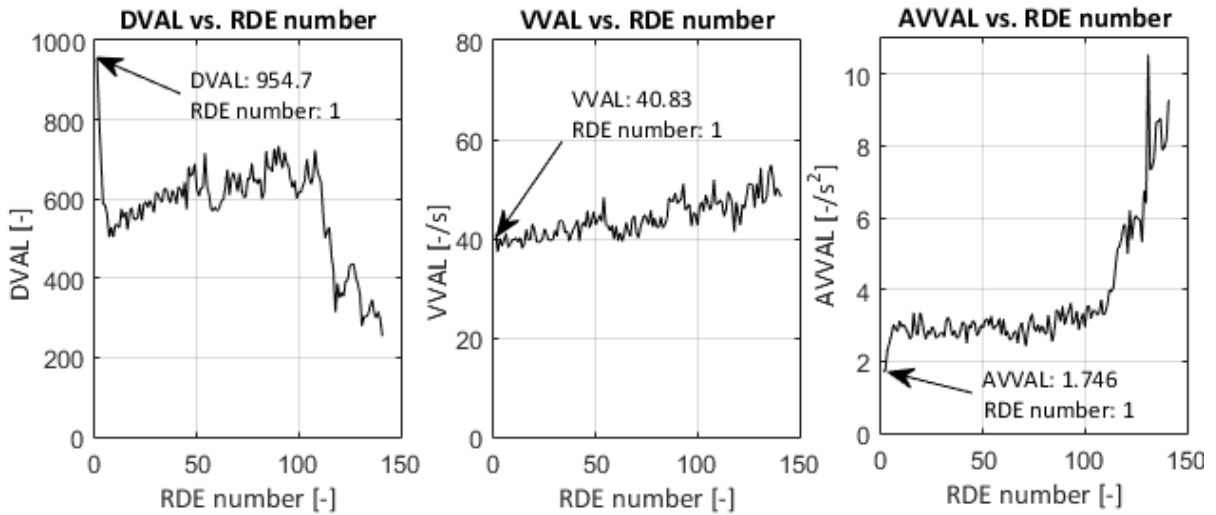


Figure 4-17: Degradation quantified during a rolling motion

Figure 4-18 shows the calculated $DVAL$, and $AVVAL$ values during a rolling motion for four different sets of BBs subjected to numerous RDEs until failure occurred.

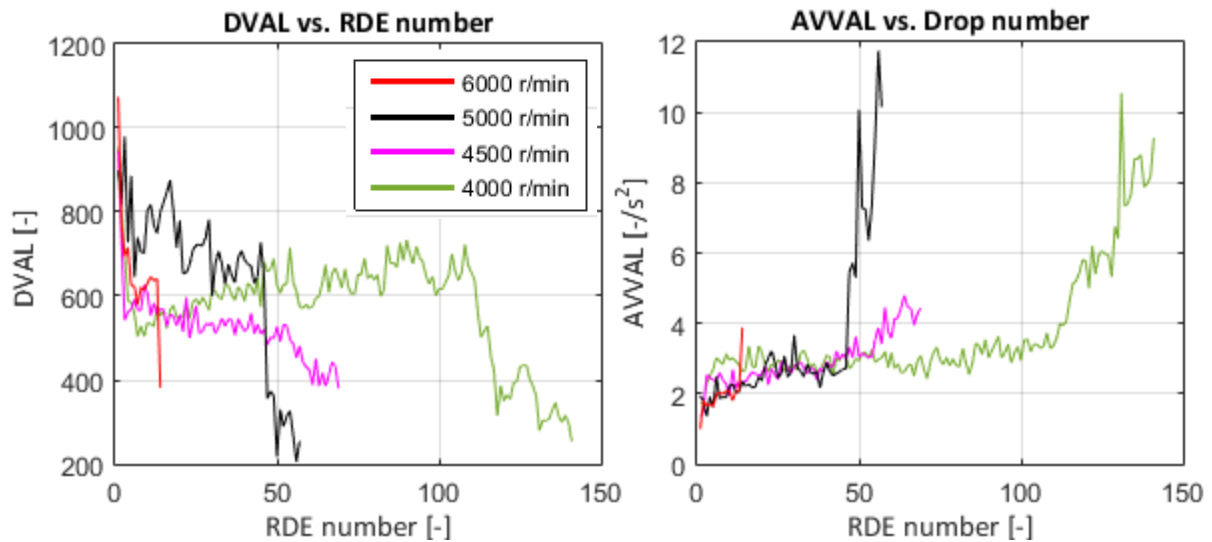


Figure 4-18: Degradation quantified during a rolling motion for multiple conditions

In contrast to case A and B, a large decrease in *DVAL* and increase in *AVVAL* occur before catastrophic bearing failure. The large peaks of the individual curves provide some information on the RDE number where sudden increases in rolling friction occur. The increased rolling friction decreases the time over which the rolling motion occurs. The sudden decreased duration of the rolling motion causes a significantly decreased *DVAL* and increased *AVVAL* value. *VVAL* did not produce any significant results and is not shown. The magnitude of the *AVVAL* values before failure remains rather consistent independent of the delevitation condition. *AVVAL* will be used for failure detection purposes due to the dependency on both time and transverse movement. The red dots in Figure 4-19 show the RDE numbers at which suspected bearing failure occurred for the results found in Figure 4-18.

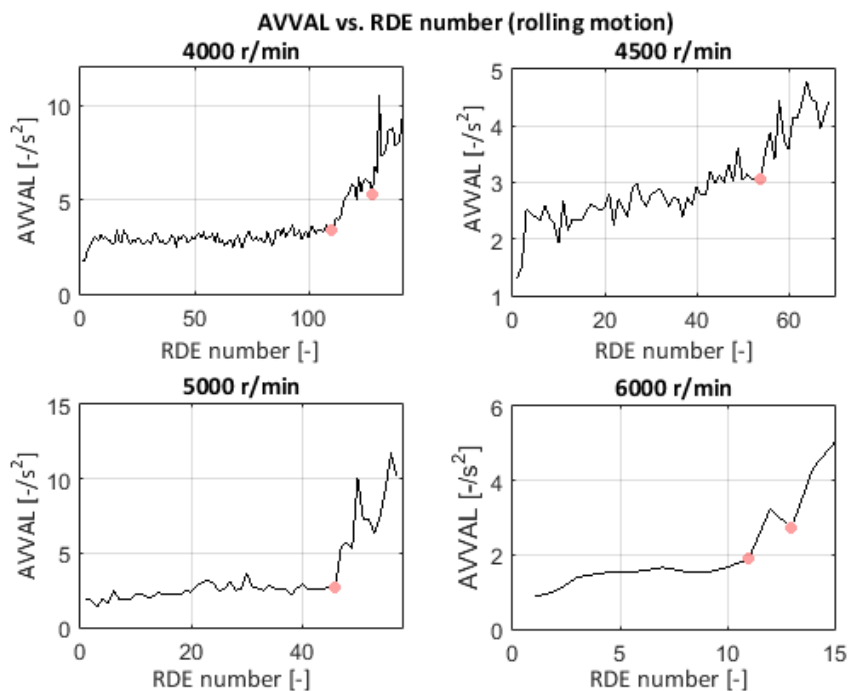


Figure 4-19: Failure detection of BBs using *AVVAL*

4.4 Discussion

Within this chapter, the usability of delevitation severity indicators for quantifying degradation was investigated. A general lack of information regarding the use of delevitation severity indicators for degradation quantification was found to exist. Various studies had to be performed to find a method for using delevitation severity indicators for life prediction and failure detection purposes.

Calculating delevitation severity indicators over the entire RDE yielded no clear application for life prediction capabilities. To solve this issue, an investigation into the effect of different rotordynamic motions on delevitation severity indicators was done. A distinctive linear pattern of degradation was identified by calculating *AVVAL* for the duration when rotor whirl and bouncing occurred. A threshold BB failure value was also identified. The distinctive pattern of degradation and identified threshold failure value will be used to formulate a life prediction method.

Large and sudden changes in rolling friction were detected by calculating the values of *DVAL* and *AVVAL* for the duration when a rolling motion is induced. The changes serve as an early warning for possible catastrophic failure of the bearing and enable a form of BB failure detection. The identified failure detection method will be used to determine when BB had occurred. Table 4-1 shows a summary of each delevitation severity indicator regarding its individual BB life prediction and failure detection capabilities.

Table 4-1: Capability comparison of delevitation severity indicators

Delevitation severity indicator	Life prediction capabilities	Failure detection capabilities
DVAL	x	✓
VVAL	x	x
AVVAL	✓	✓

Validation and verification of the failure detection method will be investigated in Chapter 6.

Chapter 5

Usefulness of severity indicators for life prediction

This chapter contains the formulation of two individual methods for predicting BB life. The two methods are based on the experimental results in Chapter 3 and are named the safe envelope method (SEM), and the linear extrapolation method (LEM). The capabilities and restrictions of these methods are also investigated.

5.1 Introduction

Calculating delevitation severity indicators for multiple RDEs over the duration when rotor motion is most severe revealed a threshold after which BB failure occurs. The energy dissipated by the BBs during an RDE is an indication of the degradation of bearing quality caused by delevitation of the rotor [11]. The *AVVAL* threshold suggests a maximum cumulative amount of energy that the rolling elements can absorb before failure occurs. Determining the threshold value for any bearing falls beyond the bounds of this research and a method for predicting BB life will be based on a sufficiently characterised BB system. From the results in Chapter 4, two possible methods for predicting BB life are identified. These methods will now be discussed.

The first BB life prediction method is based on a combination of statistical bearing failure distributions, identified linear degradation patterns, and distinct threshold values from Section 4.3.3.1. A linear fit is applied to the bearing degradation pattern to predict probable bearing failure. This method will be referred to as the safe envelope method (SEM).

The second method is formulated from statistical bearing failure distributions and involves using the cumulative sum of the *AVVAL* values at failure to generate a failure distribution curve. The failure distribution curve is used to predict bearing life based on the cumulative *AVVAL* remaining after an RDE at a specific initial condition had occurred. This method will be referred to as the linear extrapolation method (LEM).

5.2 Safe envelope method

The SEM predicts BB life based on the statistical distribution of bearing failure together with the degradation patterns identified in Section 4.3.3.1. Three identified zones are used to assess the condition of a bearing. The zones are labelled the danger zone, failure zone and the critical failure zone and are shown in Figure 5-1.

The danger zone is obtained from a linear fit at the *AVVAL* values when suspected bearing failure occurred. Bearing failure is not expected to occur before this line. Bearing operation is considered safe when the *AVVAL* values are above this zone.

Most of the bearing failure occurred between the failure zone and critical failure zone lines. From the RDE results shown in Figure 5-1, it was calculated that 83% of the BB failures occurred between the respective zones. Most of the catastrophic bearing failures are expected to occur after the failure zone line is traversed.

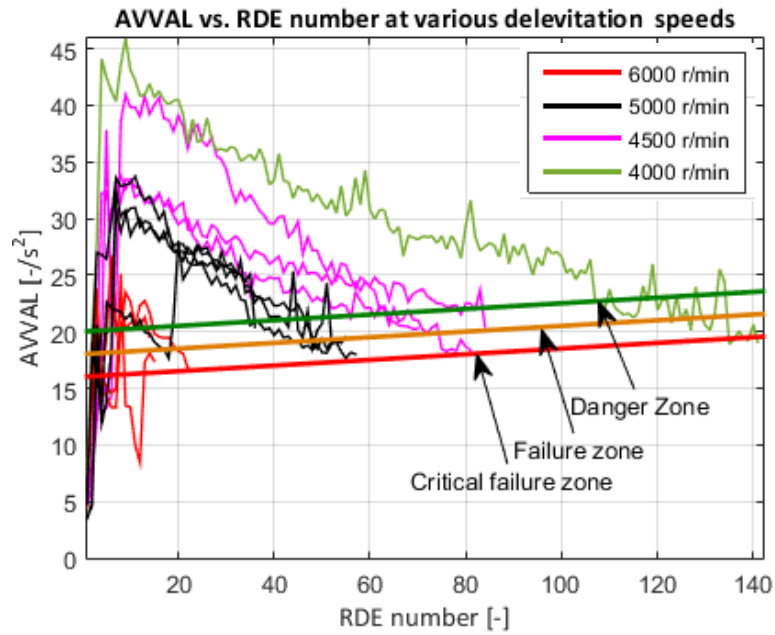


Figure 5-1: Failure zones of the safe envelope method for BB life prediction

Figure 5-2 shows an example of how the SEM is used to predict BB failure based on the rotor delevitation history. A linear fit is applied to the AVVAL values obtained from the first few RDEs after bearing run-in occurred. This linear fit is then used to determine the intersection with the danger zone line. The danger zone line is used because the experimental work of this study has shown that bearing failure does not occur above this line. The danger zone can be used to analyse if safety during delevitation can be sustained.

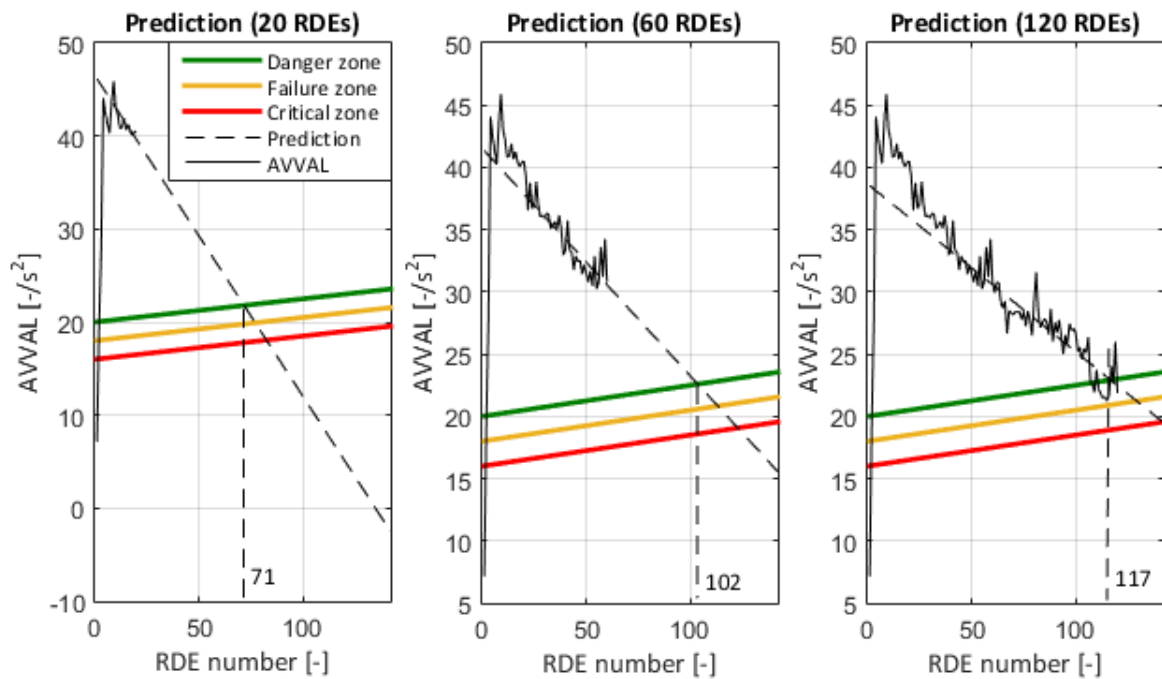


Figure 5-2: Safe envelope method - prediction example

The SEM relies on a relatively large RDE history before predictions can be made. The following section investigates the settling time (number of RDEs) required by the SEM to predict bearing life.

5.2.1 Safe envelope method settling time

Figure 5-3 shows the predicted BB life after each delevitation for a bearing subjected to a total of 142 delevitations at 4000 r/min before failure occurred. Plotting the predicted BB life after each delevitation against its respective RDE number yields the settling time required by the SEM. The suspected failure location was obtained using the method described in Section 4.3.3.3.

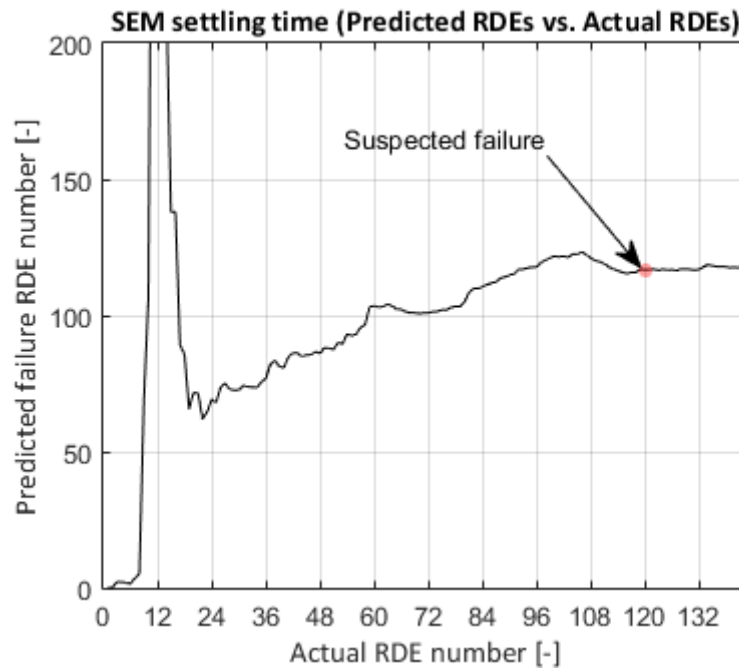


Figure 5-3: Safe envelope method settling time

Figure 5-3 shows an RDE requirement of at least 18 RDEs before predictions can be made. The bearing run-in phase does not allow the SEM to establish early linear trends within the delevitation data. Similar results were found at other initial conditions where a maximum of 20 and a minimum 16 RDEs were required to predict BB life. The individual settling times for various initial conditions can be found in Appendix B. The SEM was deemed inapplicable for delevitation speeds exceeding 6000 r/min. Bearing failure at delevitation speeds above 6000 r/min occurs before complete bearing run-in occurs and prevents the SEM from establishing linear trends within the BB degradation data. To counter this problem, a linear extrapolation method is formulated and discussed within the following section.

5.3 Linear extrapolation method

To circumvent the requirement for a large number of RDEs, the linear extrapolation method (LEM) is formulated. This method is used in collaboration with the SEM to improve its functionality. The LEM involves calculating the cumulative sum of the *AVVAL* values after each RDE and comparing them to a predetermined system failure curve. The formulation of the LEM will now be discussed.

Figure 5-4 shows the cumulative *AVVAL* delevitation results for a bearing subjected to a total of 142 delevitations at 4000 r/min until catastrophic failure of the bearing cage occurred. The cumulative

AVVAL is plotted against the inverse of the RDE number to give a representation of the number of RDEs remaining after a certain AVVAL value is reached. The moment of suspected low-severity failure is determined using the method described in Section 4.3.3.3.

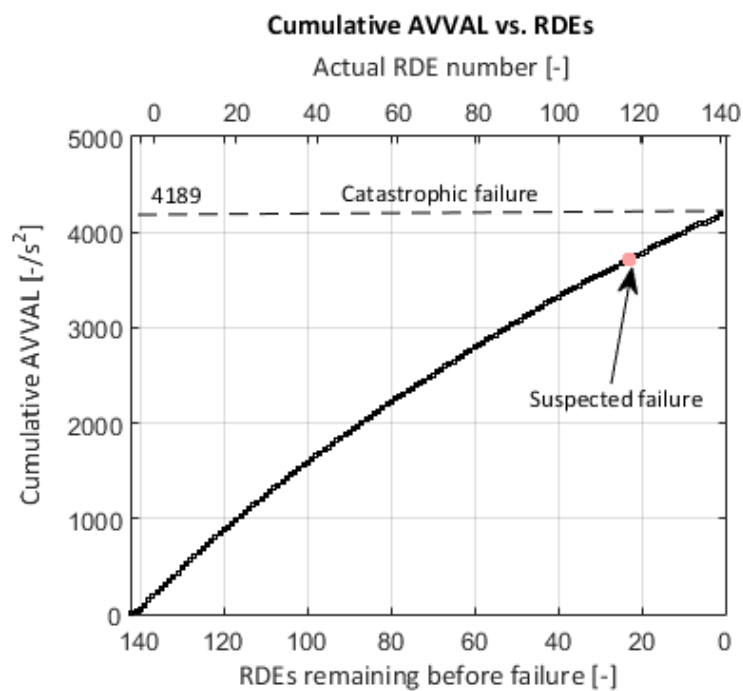


Figure 5-4: Cumulative AVVAL after each RDE until bearing failure

Closer inspection of Figure 5-4 yields the maximum cumulative AVVAL value at the moment when catastrophic bearing failure occurs. Figure 5-5 shows similar cumulative AVVAL patterns for bearings subjected to different delevitation conditions. Each curve represents a different set of bearings subjected to numerous RDEs until catastrophic failure of the bearing cage occurred.

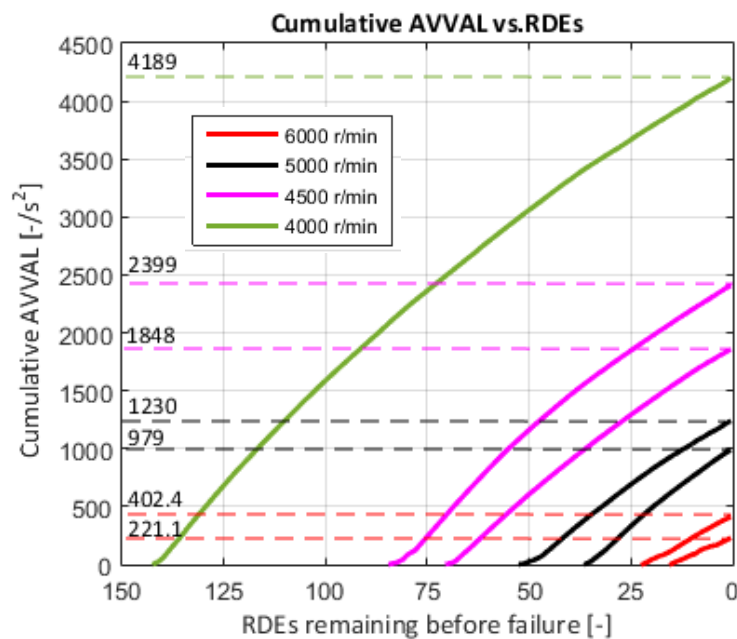


Figure 5-5: Cumulative AVVAL after each RDE until bearing failure for multiple delevitation conditions

Figure 5-6 shows the maximum cumulative *AVVAL* value at failure plotted against its respective delevitation condition. Plotting the maximum cumulative *AVVAL* value at failure against its respective delevitation condition yields a failure curve similar to the one in Figure 3-7.

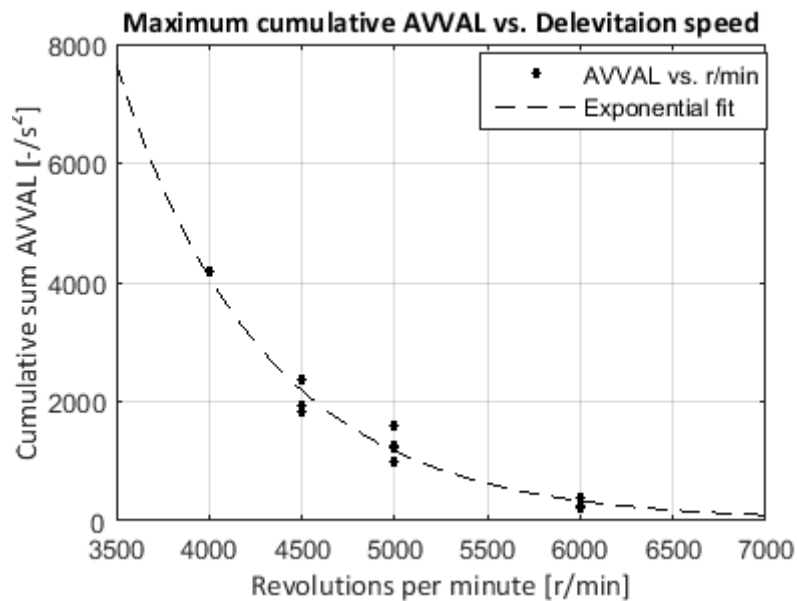


Figure 5-6: *AVVAL* failure curve

From Figure 5-6 exponential relationship between the delevitation speed and the maximum cumulative *AVVAL* value at failure can be obtained. Equation (5.1) shows the exponential relationship with N the speed at which the rotor is delevitated.

$$AVVAL_{\max} = 6.1105 \cdot e^{(-0.001252 \cdot N)} \quad (5.1)$$

If the speed at which the rotor is delevitated is known, the exponential equation is used to determine the maximum cumulative *AVVAL* value required for a bearing to fail under the same repeated delevitation conditions.

Subtracting the cumulative *AVVAL* value after each RDE from equation (5.1) yields the total cumulative *AVVAL* remaining before failure is likely to occur. Plotting the calculated remaining *AVVAL* against its respective RDE number yields a linear trend that can be used to predict the RDE number at which failure is likely to occur. Figure 5-7 shows an example of how a linear fit is used to predict BB life under a specific set of initial conditions. The suspected failure location was determined using the method in Section 4.3.3.3.

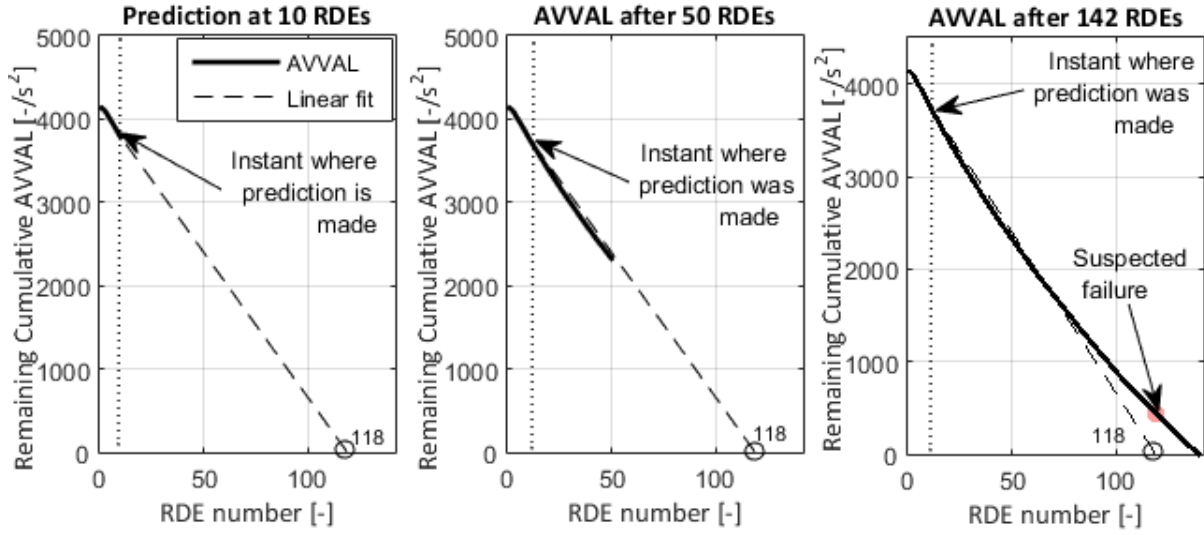


Figure 5-7: Linear extrapolation method linear fit example

It is important to note that the linear fit is unique for each specific set of BBs. The gradient of the curve automatically corrects any large deviation in BB life prediction. The straight-line equation used to predict the number of RDEs until failure is given by

$$RDE_{failure} = \frac{(AVVAL_{max} - AVVAL_{sum})}{m_{curve}} \quad (5.2)$$

with m_{curve} the gradient of the curve, $AVVAL_{max}$ the $AVVAL$ value determined using (5.1), $AVVAL_{sum}$ the cumulative $AVVAL$ value after each delevitation, and $RDE_{failure}$ the predicted RDE number where failure will occur. As with the safe envelope method, the settling time of the linear extrapolation method is investigated

5.3.1 Linear extrapolation method settling time

Figure 5-8 shows the predicted BB life after each delevitation for a bearing subjected to a total of 142 delevitations at 4000 r/min before failure occurred. Closer inspection of this figure reveals that the LEM required eight delevitations before bearing life could be predicted. Appendix B shows similar results for bearings subjected to different delevitation conditions where a maximum of twelve RDEs were required for predictions to be made. In contrast to the SEM, the LEM was applicable to delevitations above 6000 r/min.

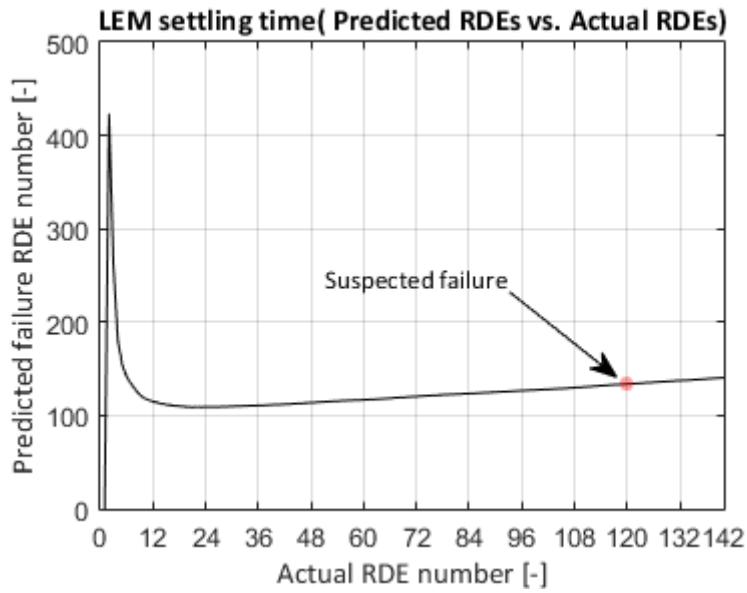


Figure 5-8: Linear extrapolation method settling time

5.4 Discussion

Within this chapter, two methods for predicting BB life were formulated. The safe envelope method (SEM) involved comparing the *AVVAL* values from a rotor delevitation history to predict linear degradation patterns. This SEM not only demonstrates life prediction capabilities but also some application for preventative maintenance. Disadvantages of the SEM include the requirement of a large number of RDEs and limited functionality at high rotor delevitation speeds. To counter the disadvantages associated with the SEM, the linear extrapolation method was formulated.

The linear extrapolation method (LEM) involved comparing the cumulative sum of the *AVVAL* values to a predetermined system failure equation. Although this method solved some of the problems associated with the SEM, the equation used to compare the actual *AVVAL* values is unique for each BB system. The user will be required to characterise BB failure in a sufficient manner to obtain a bearing failure curve that can be used to predict BB life. The main advantage of this method is the ability to predict bearing life within the first few RDEs. Based on the obtained LEM settling times, LEM life prediction will be applied after the first twelve RDEs occurred.

Chapter 6

Validation and Verification

This chapter explains verification of the relationship between AVVAL and BB degradation. Verification of the method used to analyse system critical frequencies is also discussed. Validation of BB life prediction and failure detection methods is also presented.

6.1 Verification

The results in Chapter 4 showed that delevitation severity indicators change as the bearing degrades. A distinctive linear degradation pattern was identified by calculating AVVAL during the period of most severe rotordynamic motion. The relationship between AVVAL and rolling friction is studied to demonstrate that AVVAL provides an indication of bearing degradation. The relationship between the non-dimensionalised distance (DVAL) and the time during which the delevitation occurs is also studied. This relationship is investigated since AVVAL is a function of both time and transverse movement. Verification of the method used to analyse the system critical frequencies is also performed.

6.1.1 Relationship between AVVAL and rolling friction

The coefficient of rolling friction is calculated during the period where persistent contact between the rotor and the bearing inner-race is maintained (rolling motion). This method relies on the assumption that at lower speeds, losses are confined to the BBs. Solving (6.1) for μ yields the coefficient of rolling friction

$$\tau_{friction} = I_{Rotor} \cdot \alpha_{Rotor}, F_{friction} = \frac{\tau_{friction}}{R_{Rotor}}, \mu = \frac{F_{friction}}{m_{rotor} \cdot g} \quad (6.1)$$

The coefficient of rolling friction is

$$\mu = \frac{I_{Rotor} \cdot \alpha_{Rotor}}{R_{rotor} \cdot m_{rotor} \cdot g}, \quad (6.2)$$

where μ is the coefficient of rolling friction, I_{Rotor} the moment of inertia of the rotor, R_{rotor} the radius of the rotor, α_{Rotor} the rotational acceleration of the rotor, m_{rotor} the total mass of the rotor and g the gravitational acceleration [12].

Bearing degradation is studied by calculating and comparing the average coefficient of rolling friction for each RDE of a bearing subjected to multiple RDEs until failure. The change in rolling friction indicates a change in bearing performance characteristics. Figure 6-1 shows the calculated coefficient of friction of each RDE for two separate sets of BBs tested until failure.

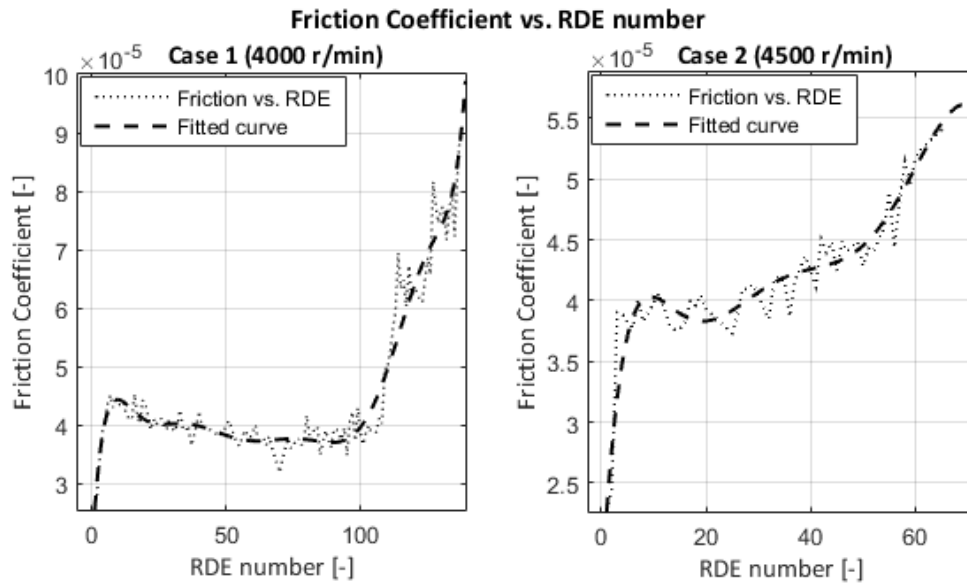


Figure 6-1: Change in bearing friction over a series of RDEs

Closer inspection of Figure 6-1 reveals that both cases present a very low friction coefficient within the first few RDEs. After approximately 10 RDEs, an almost constant friction coefficient for Case 1 is obtained after the bearing has effectively been run in. The slight downwards trend can be attributed to bearing cage wear that effectively reduces contact friction between bearing ball, cage, inner and outer-race interfaces. Once bearing wear reaches a point where the rotational movement of the bearing is hindered, the friction factor sharply increases. By determining the friction coefficient of the bearing, the effect of bearing degradation on delevitation duration and transverse movement can further be studied. This relationship is studied since *AVVAL* is a function of both time and the non-dimensionalised distance travelled (*DVAL*). In Chapter 3 it assumed that an increase in friction is proportional to a decrease in time and/or rotor movement.

Figure 6-2 (left) shows the relationship between the calculated friction coefficients and its respective RDE delevitation times. Figure 6-2 (Right) shows the relationship between the calculated friction coefficient and the non-dimensionalised distance travelled by the rotor for Case 1 in Figure 6-1.

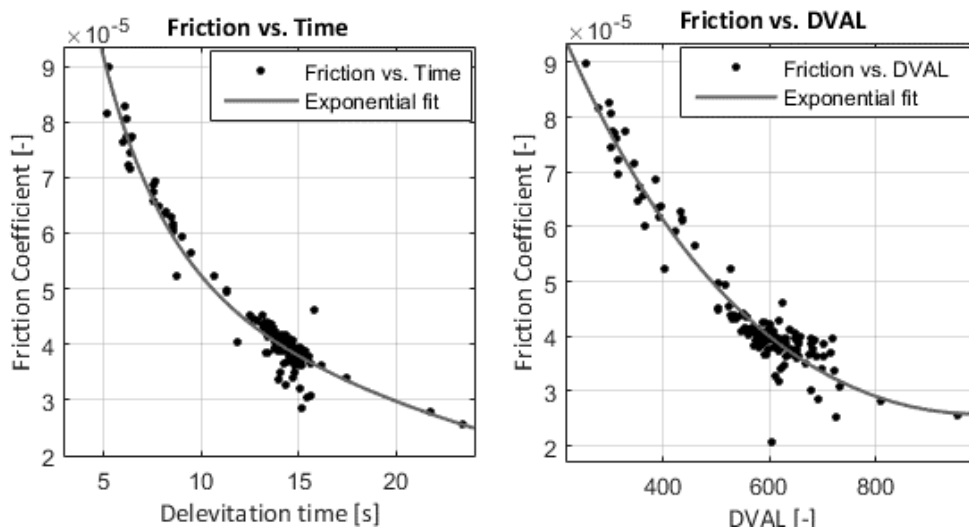


Figure 6-2: Effect of bearing friction on delevitation duration and transverse movement

Figure 6-2 reveals that an increase in bearing friction results in an exponential decrease in both delevitation duration and *DVAL*. Because of the exponential relationship between *DVAL* and friction, and the exponential relationship between the delevitation time and friction, *AVVAL* will have a linear relationship with the friction coefficient. Figure 6-3 shows the relationship between *AVVAL* and bearing friction for 705 individual RDEs induced at various delevitation conditions.

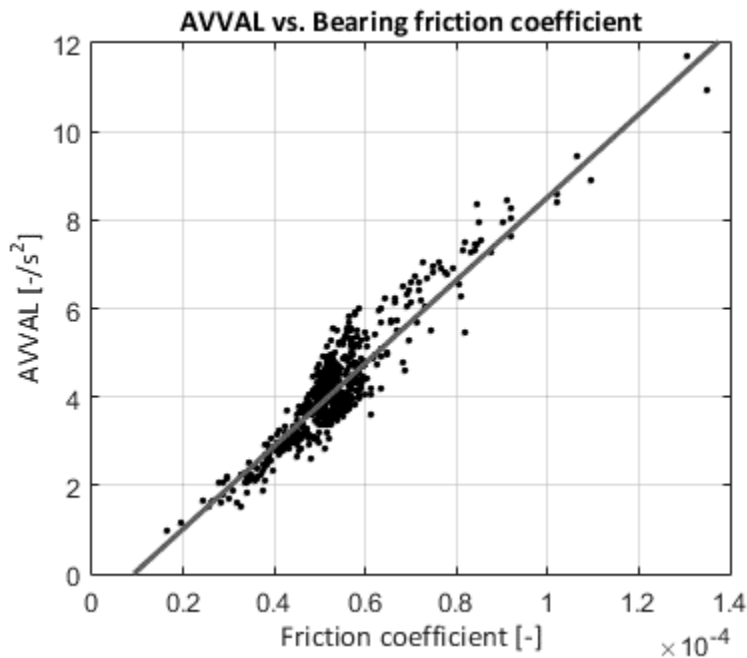


Figure 6-3: Relationship between *AVVAL* and bearing friction

Closer inspection of Figure 6-3 reveals that, as predicted, a linear relationship between *AVVAL* and bearing friction exists. As the bearing friction increases, *AVVAL* increases in a similar manner. From this figure, it can be seen that the linear fit does not intersect the *x*-axis at zero. The non-zero intersection exists because rotor movement is possible only after overcoming static friction. An increase in bearing friction, associated with a higher RDE number, can also be attributed to numerous types of damages found within the bearing raceway and rolling elements. Bearing damage types were studied by means of a scanning electron microscope.

Figure 6-4 shows scanning electron microscope imagery obtained during the experimental investigation of this study. This figure shows two separate instants within bearing life. Figure 6-4 (left) denotes bearing condition before RDE exposure. Figure 6-4 (right) denotes bearing condition after 142 delevitations for the non-failed bearing of a BB set where one of the bearings failed.

No evidence of brinelling, spalling and/or fretting within the bearing components could be found. Damage was mostly limited to debris and contamination within the bearing raceway. Some evidence of smearing was found in the cage pockets. The bearing damage types provide evidence of poor lubrication, sudden-acceleration damage, cage to inner-race contact, damage caused by large-amplitude vibration, and contamination damage.

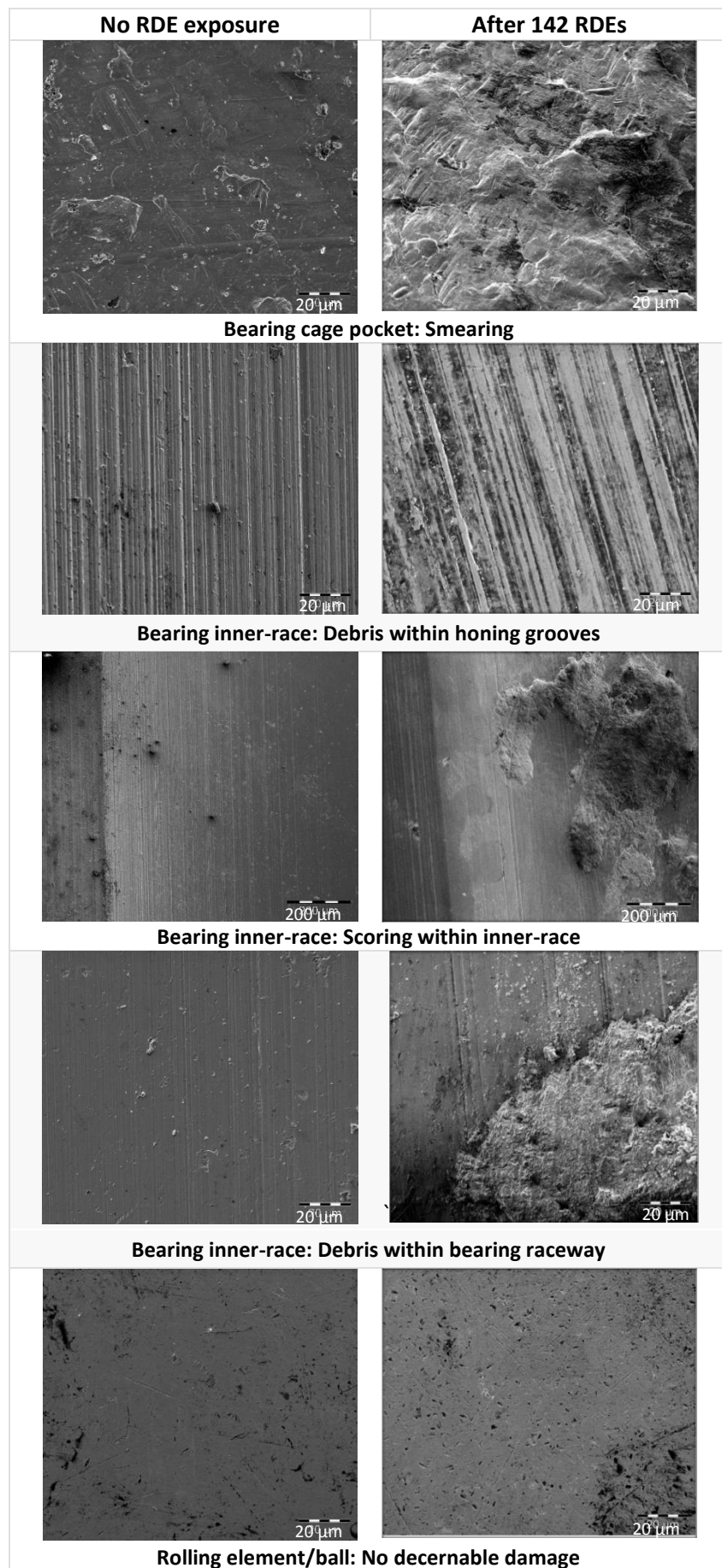


Figure 6-4: Bearing damage - Scanning electron microscope images

6.1.2 Relationship between delevitation duration and *DVAL*

A method to predict BB life is based on the observed linear degradation patterns and threshold values. *AVVAL* is a function of both time and transverse movement. The relationship between the non-dimensionalised distance (*DVAL*) and the delevitation duration is studied to provide an explanation to the observed linear degradation patterns.

Figure 6-5 (left) shows the calculated *DVAL* of each RDE for a BB subjected to 142 RDEs until failure. Figure 6-5 (right) shows the duration of each delevitation against its respective RDE number.

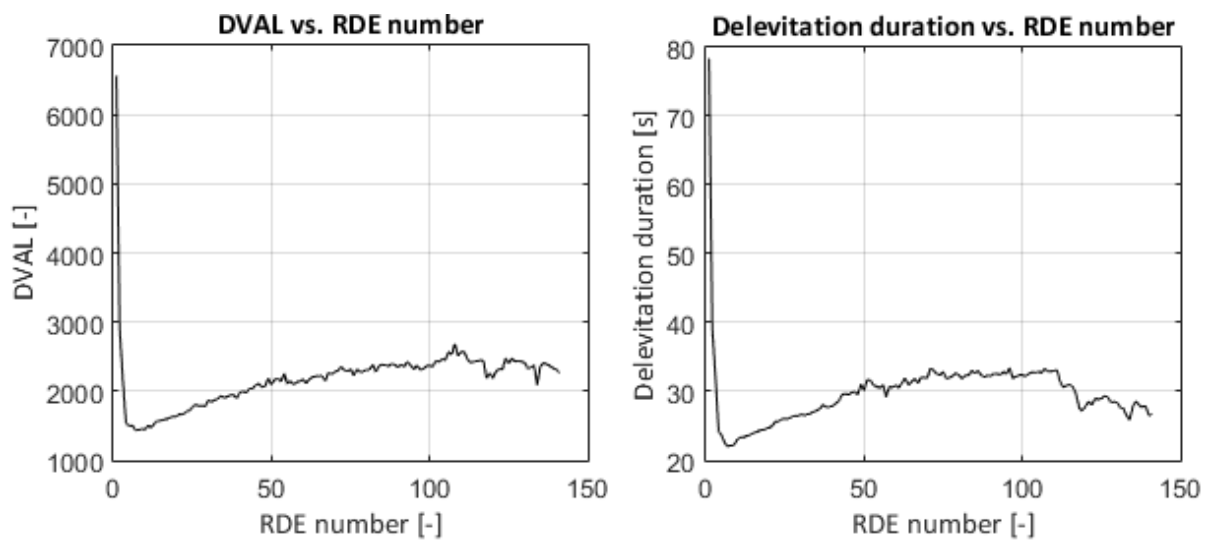


Figure 6-5: Non-dimensionalised distance (left) and delevitation duration (Right) for each RDE of a bearing subjected to 142 RDEs at 4000 r/min until failure

Figure 6-5 shows that *DVAL* and the delevitation duration both increase as the RDE number increases before decreasing. It is also clear that the first few RDEs have the largest transverse movement and longest delevitation duration. The relationship between these variables will now be studied. Figure 6-6 shows the relationship between *DVAL* and the delevitation duration for 705 individual delevitations induced at initial conditions varying from 4000 – 6000 r/min.

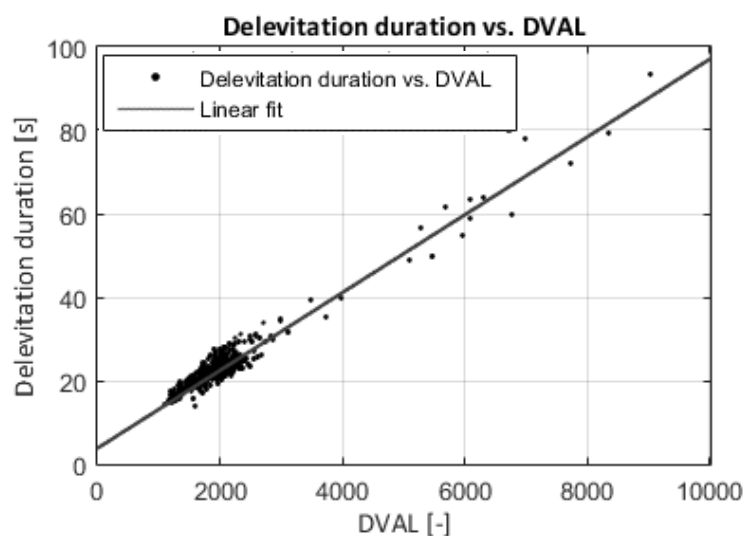


Figure 6-6: Relationship between delevitation duration and *DVAL*

Figure 6-6 shows a linear relationship between the non-dimensionalised distance and the delevitation duration. The few data points at higher $DVAL$ values can be attributed to the increased delevitation durations associated with bearing run-in. A stationary RDE will have a $DVAL$ value of approximately 0.5 and a delevitation duration equal to the time required for the rotor to travel half the airgap distance. The linear fit is thus expected to intersect the x - and y -axis close to zero. The slight offset from zero is caused by position sensor noise. The formulation of $DVAL$ causes the position sensor noise to have a cumulative effect on the magnitude of $DVAL$.

The linear relationship between $DVAL$ and the delevitation duration will cause any change in delevitation duration to have a non-linear influence on the magnitude of $AVVAL$. The non-linear influence of the delevitation duration can be attributed to the formulation of $AVVAL$ (equation (3.6)). Figure 6-7 shows an exponential relationship between delevitation duration and $AVVAL$ for 705 RDEs at various delevitation conditions.

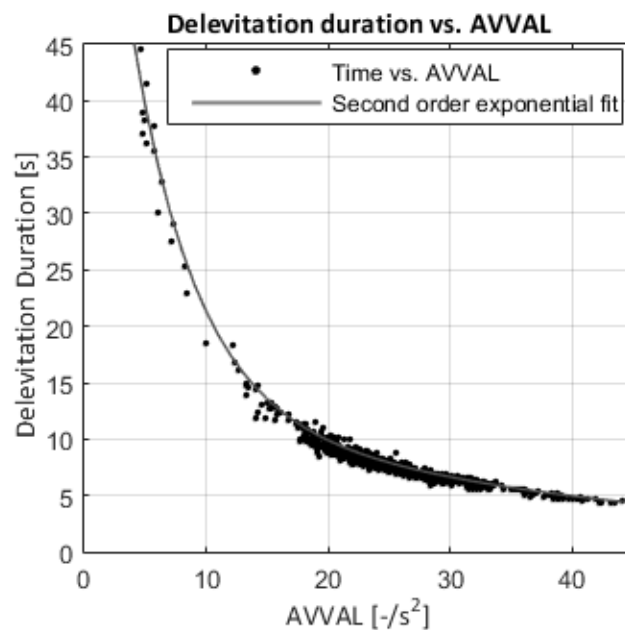


Figure 6-7: Relationship between delevitation duration and $AVVAL$

It is clear from Figure 6-7 that an exponential relationship between the delevitation duration and $AVVAL$ exists. The exponential relationship between the squared delevitation time and $AVVAL$ might explain the linear degradation pattern obtained for life prediction purposes.

6.1.3 Critical frequency analysis verification

The formulated life prediction methods rely on the formulated critical frequency analysis methods in Section 4.3.2. Verification of the critical frequencies is achieved by means of a spectral decay plot. A spectral decay plot allows investigation of changes in the frequency spectrum with changes in rotational speed. Calculations for the spectral decay plot can be found in Appendix E.

Plotting $\Delta DVAL$ against rotor speed yields the rate at which the airgap distance is traversed by the rotor at various rotational speeds. Figure 6-8 shows $\Delta DVAL$ for a single delevitation induced at 5000 r/min. The peaks within the plot denote the system critical frequencies.

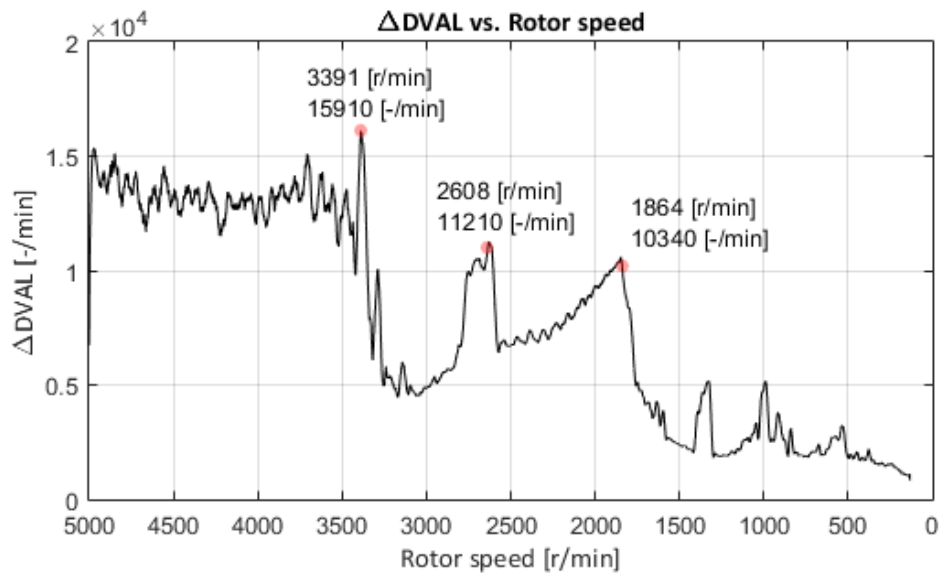


Figure 6-8: $\Delta DVAL$ critical frequency analysis

Figure 6-9 shows the spectral decay plot of the same RDE found in Figure 6-8.

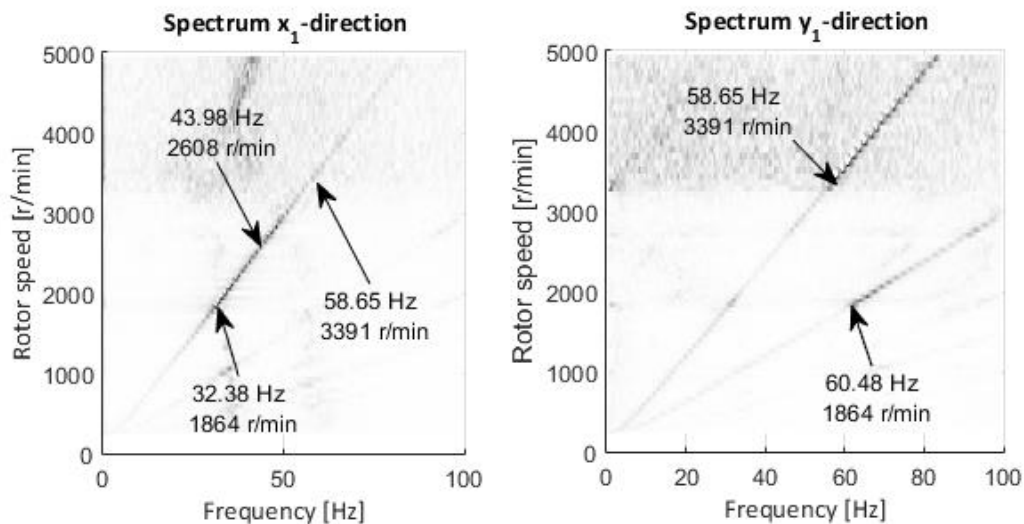


Figure 6-9: Spectral decay plot critical frequency analysis

From Figure 6-9, it can be seen that the rotor exits the rotor-bearing system's third y-direction critical frequency at approximately 3391 r/min. The rotor enters the third x-direction critical frequency at approximately the same speed at 3391 r/min. The rotor's second y-direction critical frequency is at approximately 2608 r/min. The maximum critical frequency amplitude for the x-direction's third critical frequency is at approximately 2608 r/min. The second y-direction critical frequency ends at approximately 3391 r/min. Comparing the spectral decay plot with Figure 6-8, it should be clear that the critical frequencies are aligned with increased transverse movement. This alignment implies that the frequencies are system critical frequencies. It is also interesting to note that the instant when forward whirl occurs is when the second y-direction frequency ends and the second x-direction critical frequency begins.

6.2 Validation of failure detection method

This section contains validation results for the failure detection methods used to detect suspected bearing failure. All of the results presented were experimentally obtained using the setup and methods described in in Chapter 3.

6.2.1 Failure detection validation

The method used to detect BB failure is described in Section 4.3.3.3. Validation is achieved by subjecting a set of BBs to various RDEs. Delevitation severity indicators after each RDE are calculated for the duration of a rolling motion (1000 – 0 r/min) to detect sudden changes in rolling friction. If a sudden change in the magnitude of delevitation severity indicators is detected, the bearings are removed for inspection purposes.

Figure 6-10 shows the quantification results for two separate sets of BBs subjected to numerous RDEs until suspected failure occurred. Figure 6-10 (left) shows the results of a bearing subjected to repeated 4000 r/min delevitations. Figure 6-10 (right) shows the results of a bearing subjected to random delevitation conditions ranging between 3000 -6000 r/min

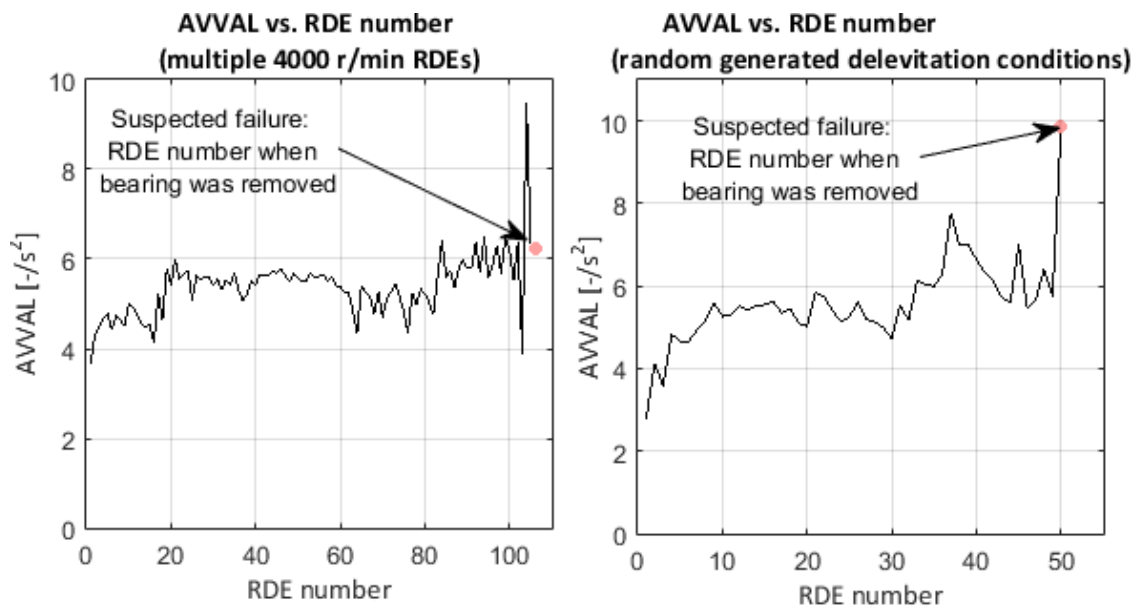


Figure 6-10: Failure detection validation

The BBs were removed for inspection purposes at the RDE number of suspected bearing failure. Figure 6-11 shows the BBs at the suspected failure RDE numbers found in Figure 6-10.

Figure 6-11 reveals that the failure detection methods were able to detect when bearing cage failure occurred. Delevitated shaft hand roll checks during this study were ineffective for detecting low severity bearing failure. Hand roll checks were only able to detect bearing failure for the bearing subjected to random delevitation conditions. Hand roll checks for the bearing subjected to multiple 4000 r/min delevitations revealed no clear indication of increased rolling resistance.

**Bearing at suspected failure for multiple
4000 r/min delevitations**



**Bearing at suspected failure for random
delevation conditions**



Figure 6-11: Inspection of bearings at suspected failure

Appendix B contains results for the failure detection methods applied to the RDE results from Chapter 3. These results reveal that the BBs were exposed to multiple RDEs even after possible low-severity cage failure had occurred. The RDE exposure after low-severity failure caused complete seizure of the rolling elements. The failure detection methods were only effective for detecting low-severity bearing failure in 75% of the cases

6.3 Validation of life prediction methods

This section contains validation results of both the SEM and LEM methods. Validation is achieved by inducing multiple RDEs at various delevitation conditions and comparing the predicted number of RDEs to the number of RDEs when bearing failure is suspected. All of the data presented within this chapter were experimentally obtained using the setup and methods described in in Chapter 3.

6.3.1 Bearing failure results summary

Table 6-1 shows a summary of the experimental results used for validation purposes. Bearings from two different manufacturers were repeatedly subjected to various delevitation conditions until catastrophic bearing failure occurred. The manufacturers are named manufacturer A and manufacturer B and contain different cage designs. Additionally, Table 6-1 shows the RDE number where suspected bearing failure occurred. The suspected failure results are shown in Appendix B and were determined using the methods found in Section 4.3.3.3. It is important to note that the number of RDEs at suspected failure does not necessarily reflect the RDE number when catastrophic bearing failure occurred.

Table 6-1: Bearing failure results summary

BB set	Manufacturer A 3000 [r/min]		Manufacturer B 4000 [r/min]		Manufacturer B 4500 [r/min]		Manufacturer B 5000 [r/min]		Manufacturer B 6000 [r/min]	
	Actual RDE#	Suspected RDE#	Actual RDE#	Suspected RDE#	Actual RDE#	Suspected RDE	Actual RDE#	Suspected RDE#	Actual RDE#	Suspected RDE#
1	78	60	142	128	84	77	56	46	16	16
2	47	43	112	104	70	70	37	37	15	13
3	85	84			82	82	58	46	23	18
4							53	52		

Due to the decreased bearing cage quality from the Manufacturer A bearings, high inconsistencies in bearing failure results were found at higher delevitation speeds . Failure occurred between 1 to 10 RDEs. Due to this, results at higher delevitation speeds for this specific bearing manufacturer were found unsatisfactory for validation purposes.

6.3.2 Safe envelope method validation

To calculate delevitation severity indicators according to the method described in Section 4.3.3.1, rotordynamic analyses of both manufacturer bearings are required. The variations in bearing cage quality affect the bearing stiffness and damping properties, and could result in unexpected rotor-bearing touchdown dynamics.

Figure 6-12 shows the rotordynamic analyses of both bearing manufactures using the method described in Section 4.3.2. In this figure it is shown that the manufacturer A second critical frequency is slightly lower than that of manufacturer B. Similar results were obtained for all the bearing sets in Table 6-1. According to the formulation of the SEM, delevitation severity indicators are calculated from the point of delevitation up to the rotor speeds found in Figure 6-12.

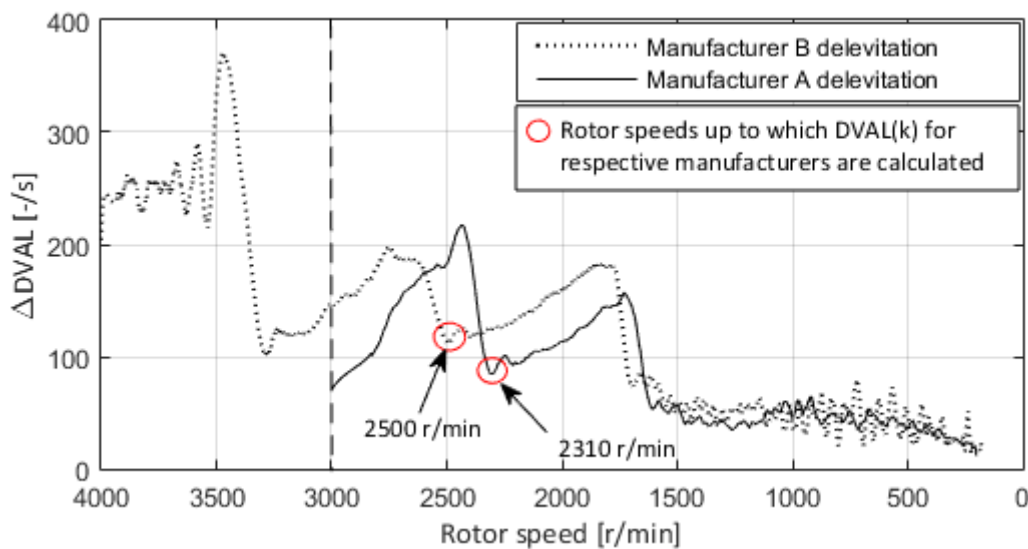


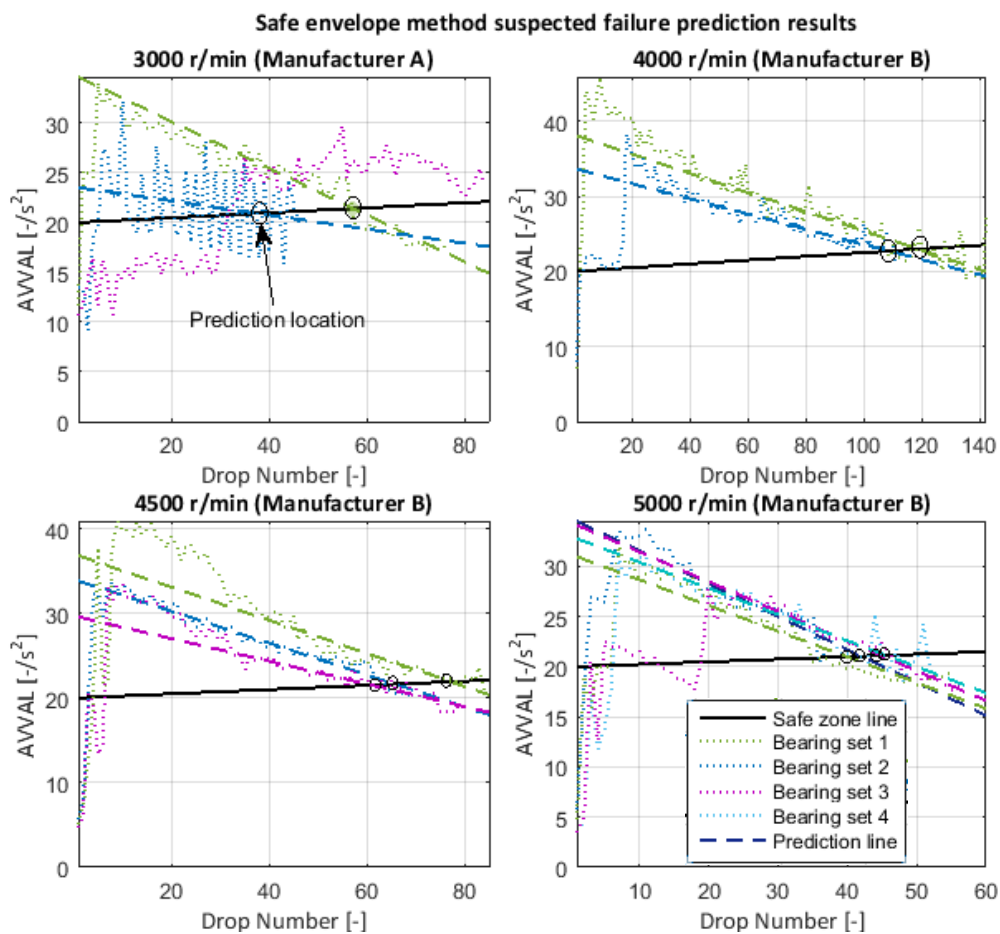
Figure 6-12: Rotordynamic analyses of different manufacturer bearings

Figure 6-13 shows the calculated AVVAL results and prediction lines of the safe envelope method used to determine the moment of bearing failure. Table 6-2 contains a summary of the suspected bearing failure results compared to the SEM prediction results. The SEM was unable to predict BB failure for high-speed delevitations (>6000 r/min). Bearing failure occurred within the settling time of the SEM at increased delevitation speeds. The results for 6000 r/min are thus not shown. The settling times can be found in Appendix B.

Table 6-2: Safe envelope method prediction results summary

Bearing set	Manufacturer A 3000 [r/min]		Manufacturer B 4000 [r/min]		Manufacturer B 4500 [r/min]		Manufacturer B 5000 [r/min]	
	Predicted RDE	Suspected RDE	Predicted RDE	Suspected RDE	Predicted RDE	Suspected RDE	Predicted RDE	Suspected RDE
1	57	60	118	118	70	82	40	46
2	39	43	109	104	65	70	41	37
3	NA	84			77	77	44	46
4							46	52

From Table 6-2 it is determined that the SEM yields an average prediction accuracy of 92% over the entire series of RDE tests. It is also important to note that 87.5% of the prediction results were found to be less than the number of RDEs when actual bearing failure occurred.



6.3.3 Linear extrapolation method validation

According to the formulation of the LEM, a predefined failure curve is used to predict bearing failure based on the cumulative *AVVAL* values over a series of delevitations. Figure 6-14 shows the cumulative *AVVAL* RDE results together with LEM lines used for life prediction purposes. Life predictions were made after the bearings were subjected to 10 RDEs. The LEM allowed predictions above 6000 r/min. The life prediction method was found inapplicable for the lower quality bearings (manufacturer A). The formulated system failure curve is bearing specific. Not enough delevitation

data were available to formulate a system failure curve for the lower quality bearings. Results for manufacturer A are thus not shown. A full discussion of the results can be found in Section 6.4.

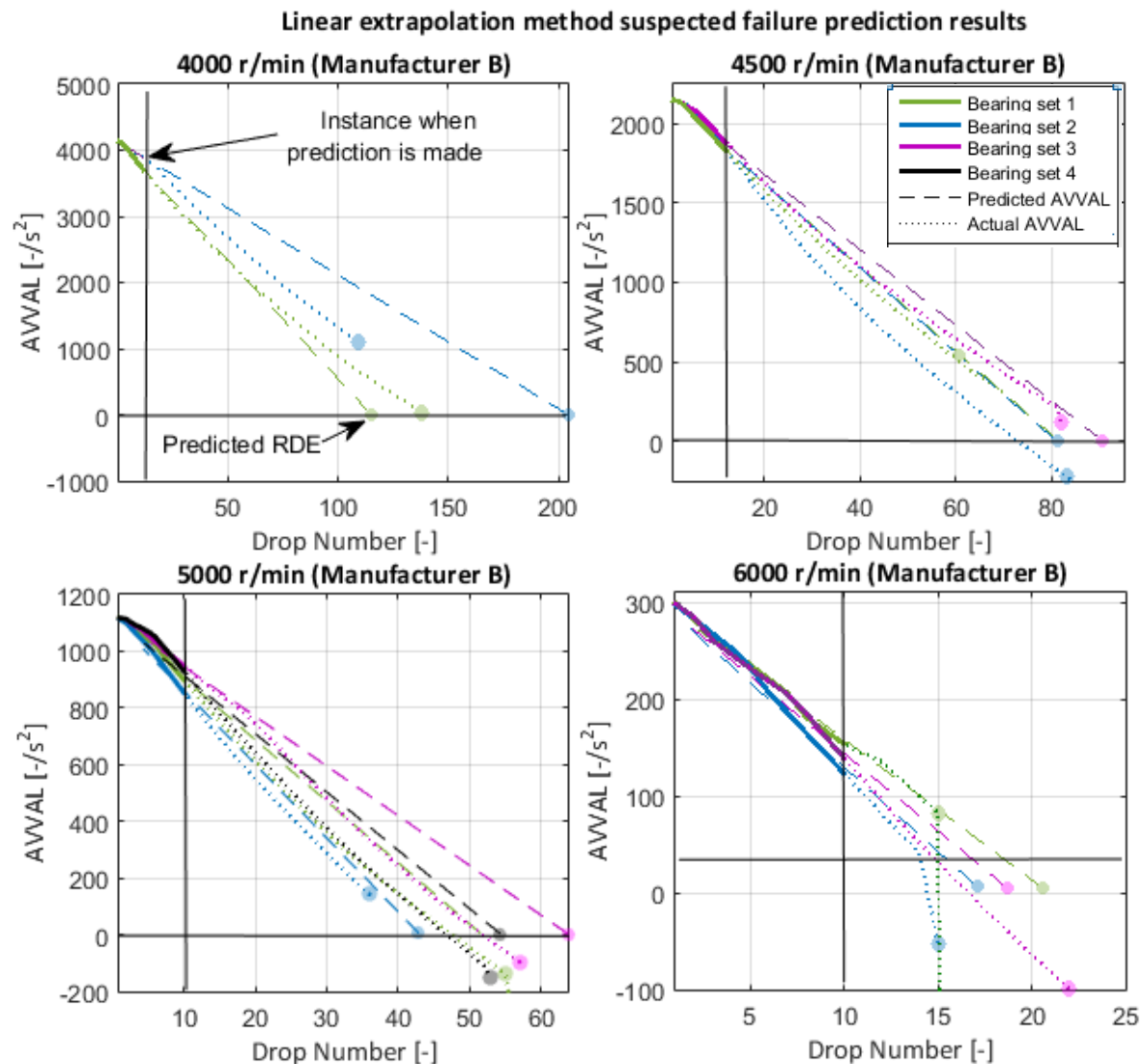


Figure 6-14: Linear extrapolation method validation results

Table 6-3 contains a summary of the suspected bearing failure results compared to the safe envelope method prediction results.

Table 6-3: Linear extrapolation method prediction results summary

	Manufacturer B 4000 [r/min]		Manufacturer B 4500 [r/min]		Manufacturer B 5000 [r/min]		Manufacturer B 4000 [r/min]	
Bearing set	Predicted RDE	Suspected RDE	Predicted RDE	Suspected RDE	Predicted RDE	Suspected RDE	Predicted RDE	Suspected RDE
1	115	118	78	77	52	46	20	16
2	202	104	80	70	42	37	16	13
3			90	82	63	46	16	18
4					54	52		

From Table 6-3 it is determined that the LEM yields an average prediction accuracy of 85% over the entire series of RDE tests. The large prediction deviation for bearing set 2 at 4000 r/min can be attributed to the formulation of the failure curve (Figure 5-6) used for life prediction purposes. The large difference between the predicted and suspected failure RDE number indicates that the exponential equation used for life prediction does not correctly fit the actual bearing failure distribution for lower speed delevitations. Prediction accuracy without the outlier was found to be 91%. From this table it is also determined that 55% of the predictions were higher than the actual number of RDEs required before bearing failure occurred. A full discussion of the results follow in Section 6.4.

6.3.4 Average of SEM and LEM

In the previous sections it is found that the safe envelope method mostly yield prediction results lower than the actual RDE results. The linear extrapolation method is found to yield prediction results mostly higher than the actual RDE results. Obtaining the average of the results found from the two methods improves the functionality and overall accuracy of the life prediction methods. Table 6-4 shows the results obtained by finding the average between the SEM and the LEM results.

Table 6-4: Optimized prediction (average of SEM and LEM)

Bearing set	Manufacture A 3000 [r/min]		Manufacturer B 4000 [r/min]		Manufacturer B 4500 [r/min]		Manufacturer B 5000 [r/min]	
	Average of LEM and SEM	Suspected RDE	Average of LEM and SEM	Suspected RDE	Average of LEM and SEM	Suspected RDE	Average of LEM and SEM	Suspected RDE
1	116	118	76	77	47	46	20	16
2			73	70	41	37	16	13
3			85	82	53	46	16	18
4					50	52		

From Table 6-4 an average prediction accuracy increase of 3% is achieved over the entire series of RDEs presented. By calculating the average prediction results between the safe envelope and linear extrapolation method a prediction accuracy of 94% is obtained.

6.4 Discussion

Within this chapter, the assumption that delevitation severity indicators yield an indication towards bearing degradation was investigated. A linear relationship between *AVVAL* and rolling friction was discovered. Because of this linear relationship, it is concluded that *AVVAL* is indicative of bearing degradation.

Various bearing damage types were visible within the ball, race and cage components. The damage types found are expected to occur within months or years of service with normal operating conditions. BB degradation occurred at a highly accelerated rate with only a few minutes of service life.

This chapter also contained verification of system critical frequency analysis using delevitation severity indicators. The system critical frequencies determined using *DVAL* and *ΔDVAL* were aligned with those frequencies determined using a spectral decay plot. The moments when the

system critical frequencies are traversed were also shown to be associated with increased transverse movement of the rotor.

Validation of the failure detection method was achieved by inducing two separate sets of BBs to multiple RDEs whilst analysing delevitation severity indicators after each RDE. The failure detection method was able to detect bearing cage failure before seizure of the rolling elements. Analysing the RDE results from Chapter 3 revealed that multiple BBs were exposed to various RDEs after low-severity failure occurred. This RDE exposure after low-severity failure caused severe backward whirl and complete seizure of the rolling elements.

Validation of the life prediction methods was achieved by inducing multiple RDEs at various delevitation conditions and comparing the predicted RDE numbers to bearing suspected failure RDE numbers. The safe envelope method and the linear extrapolation method both provided reasonable accuracy for predicting BB life.

The SEM was unable to predict BB failure for high-speed delevitations (>6000 r/min). Bearing failure occurred within the settling time of the SEM at increased delevitation speeds. Even though bearings of similar size and rating were tested with the SEM, large deviations in bearing life were observed. The only difference was the bearing cage design. The lower cage quality caused a large variation in bearing performance rendering the life prediction method less effective. In one instance, no linear trends were observed.

The LEM allowed predictions above 6000 r/min. The life prediction method was however inapplicable for the lower quality bearings. The formulated system failure curve is bearing specific. Not enough delevitation data were available to formulate a system failure curve for the lower quality bearings. The LEM was also found to be very sensitive to the formulation of the failure curve used for life prediction purposes. The LEM would only be usable on a sufficiently characterised AMB system.

For the purpose of life prediction, the SEM was found to produce most desirable results. The SEM was found usable for different bearing manufacturers. This method was also found usable for a range of delevitation conditions and allows some form of preventative maintenance capabilities.

Chapter 7

Conclusions and future work

The research presented within this dissertation aimed to quantify the degradative effect of multiple RDEs on a BB system using delevitation severity indicators. The results were then studied to develop/identify a method for predicting BB life. Through this investigation, multiple conclusions can be made. Firstly, bearings subjected to delevitation conditions complicates BB life prediction considerably. The complexity of this problem is quite evident considering the few literature sources that address this specific issue.

By subjecting multiple bearings to various delevitation conditions, bearing failure modes and failure distribution were studied. It was found that bearing life decreases exponentially as the delevitation speed increases. Catastrophic failure of the bearing was always a result of bearing cage failure. Catastrophic failure of the bearing always resulted in severe backward rotor whirl. It was also found that vibration induced by the rotor at bearing failure was contained to the BB assembly. However, similar failure modes on large-scale AMB systems could result in total AMB system failure. Basic failure detection methods from literature were ineffective in determining the status of bearing health. Hand roll checks, orbit plot trending, shaft position trending and/or rotational speed trending were all unable to identify bearing failure before catastrophic BB failure. AMB vendors are advised to implement some form of preventative maintenance or condition monitoring on the BB system to increase reliability and safety.

Using delevitation severity indicators to quantify bearing degradation enabled some rudimentary failure detection and life prediction capabilities. Changes in rotor-bearing touchdown dynamics were studied by comparing a series of RDEs for multiple sets of BBs. A linear pattern of degradation was identified by calculating *AVVAL* according to the most severe rotordynamic motions. From *ADVVAL*, it was concluded that the most severe rotordynamic motion was a bounce and whirl motion. The type and magnitude of rotor movement were also found to be independent of the delevitation speed. It is important to note that the identified linear degradation pattern was only observable after bearing run-in occurred.

A threshold for *AVVAL* beyond which bearing failure is likely to occur was also identified. The energy dissipated by the BBs during an RDE is an indication of the degradation of bearing quality caused by delevitation of the rotor [11]. This threshold thus provides some evidence of a maximum cumulative amount of energy that the rolling elements can absorb before failure occurs. More research on this phenomenon will be required.

From the identified linear degradation pattern and threshold, two methods for predicting BB life were formulated. The safe envelope method and linear extrapolation method both provided relatively accurate life prediction. Both methods provided improved prediction accuracy compared with methods that estimate BB failure based on a familiar bearing failure distribution. Due to the vast amount of different BB configurations, the methods developed here are only applicable to a sufficiently characterised AMB system.

Calculating delevitation severity during the timespan when a rolling motion is induced presented some early-failure detection capabilities. The failure detection method allows early detection of

bearing failure before catastrophic failure of the bearing cage. However, this method was only effective in 75% of the bearing sets tested. The research presented in this dissertation showed that monitoring delevitation position data yields potential for predictive maintenance capabilities. This result corresponds to the conclusions made by Reitsma [10] who concluded that the only potential for predictive maintenance capabilities is from monitoring shaft position data.

The variable $\Delta DVAL$ yielded a novel method for quantifying rotor movement during an RDE. This method provides a significant advantage over existing methods; the type and magnitude of rotor movement can be determined from basic position sensor data. This method also allows critical frequency analysis, whirl detection capabilities and RDE severity analysis. This method also displays potential as a verification tool for simulation-based methods.

It was found that bearing life is drastically influenced by bearing manufacturing quality. Bearings of similar rating but different manufacturers subjected to the same conditions differed considerably in overall bearing life. The significant dependence of bearing quality on overall bearing life could complicate modelling and simulation-based life prediction methods. Delevitation severity indicators allow bearings from different manufacturers to be compared for design and implementation purposes. Applicable BB degradation data, as set out in the research problem, were also generated and provide valuable data for future experimental work.

The recommended future work is summarised as follows:

- Degradation quantification of more complex BB systems
- Usability of delevitation severity indicators for quantifying degradation on full-compliment bearings and/or other cage-less ceramic bearing designs
- Investigation into the effect of additional BB-support damping on delevitation severity indicators
- Degradation quantification of lubricated bearings
- Implementation of force measurement capabilities on the BB system for verification purposes
- Investigate the integration of delevitation severity indicator with delevitation modelling techniques
- Determination of the identified $AVVAL$ threshold for bearing failure from basic system parameters

References

- [1] S. Y. Yoon, Z. Lin and P. E. Allaire, "Control of Surge in Centrifugal Compressors by Active Magnetic Bearings," Springer, Charlottesville, USA, 2013.
- [2] G. Schweitzer and H. Beuler, Magnetic bearings: theory, design, and application to rotating machinery, Verlag Berlin Heidelberg: Springer Science & Business, 2009.
- [3] K. J. Eakman, T. L. Coons, M. Andres and L. F. Miller, "Backup bearing for magnetic bearings". Patent 5,714,818, 3 Feb 1998.
- [4] G. Schweitzer, "Safety and Reliability Aspects For Active Magnetic Bearing Applications - A Survey," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 219, no. 6, pp. 383-392, 2005.
- [5] R. W. Bruce, "Auxiliary/Backup/Catcher Bearings," in *Handbook of Lubrication and Tribology: Theory and Design*, 2nd ed., vol. II, CRC Press, 2012.
- [6] J. J. Janse van Rensburg, G. van Schoor and P. A. van Vuuren, "Delevitation Modelling of an Active Magnetic Bearing Supported Rotor," in *Proceedings of the 12th International Symposium on Magnetic Bearings (ISMB12)*, Wuhan China, 2010.
- [7] E. V. Zaretsky, "A. Palmgren Revisited: A Basis for Bearing Life Prediction," 1997.
- [8] J. G. Lee, "A Nonlinear Transient Approach for Morton Synchronous Rotordynamic Instability and Catcher Bearing Life Prediction," 2012.
- [9] E. Swanson, A. Masala and L. Hawkins, "NEW ACTIVE MAGNETIC BEARING REQUIREMENTS FOR COMPRESSORS IN API 617 EIGHTH EDITION," 2014.
- [10] T. W. Reitsma, "Development of Long-Life Auxiliary Bearings for Critical Service Turbomachinery and High-Speed Motors," in *Proceedings of the 8th International Symposium on Magnetic Bearing*, Mito Japan, 2002.
- [11] J. J. Janse van Rensburg, G. Van Schoor and P. A. van Vuuren, "The characterization of the severity of rotor delevitation events: A parametric study," in *Proceedings of the 13th International Symposium on Magnetic Bearings*, Virginia USA, 2012.
- [12] J. J. Janse van Rensburg, "Delevitation modelling of an active magnetic bearing supported rotor," North-West University (South Africa). , Potchefstroom, 2013.
- [13] F. Betschon, "Design Principles of Integrated Magnetic Bearings," Zurich, 2000.
- [14] V. Lemarquand and G. Lemarquand, "Passive Permanent Magnet Bearing for Rotating Shaft," in *Magnetic Bearings, Theory and Applications*, Sciyo, 2010.
- [15] J. Ji, "Nonlinear Dynamics of Magnetic Bearing Systems," *Journal of Intelligent Material Systems and Structures*, 2008.

-
- [16] P. Anantachaisilp, D. Long, . Y. Y. Se and L. Zongli, "Control of Active Magnetic Bearings with input delay Applications in remotely controlled turbomachinery," in *53rd IEEE Conference on Decision and Control*, Los Angeles, 2014.
- [17] T. Collins, A. Masala, R. Shultz and Z. Guo, "Numerical and Experimental Results of Auxiliary Bearings Testing on a High Speed Test Rig," Worthing UK, 2013.
- [18] Calnetix Technologies, "Magnetic Bearing Components," 2015. [Online]. Available: <http://www.calnetix.com/components>. [Accessed 6 March 2015].
- [19] J. H. Kralick, "Auxiliary bearing design for active magnetic bearings". Patent 5,021,697, 4 June 1991.
- [20] E. R. Booser, CRC Handbook of Lubrication and Tribology, Volume III: Monitoring, materials, synthetic lubricants, and applications, vol. 3, CRC Press, 2010.
- [21] A. Karkkainen, J. Sopanen and A. Mikkola, "Dynamic simulation of a flexible rotor during drop on retainer bearings," *Journal of Sound and Vibration* , vol. 306 , pp. 601 - 617, 2007.
- [22] J. Sears and S. Uptigrove, "Magnetic Bearing Operating Experience," Texas.
- [23] S. R. Penfield and E. Rodwell, "Auxiliary Bearing Design Considerations for Gas-Cooled Reactors," 2001.
- [24] M. Salehi and H. Heshmat, "On the Dynamic and Thermal Performance of a Zero Clearance Auxiliary Bearing (ZCAB) for a Magnetic Bearing System," *Tribology Transactions*, vol. 43, no. 3, pp. 435 - 440, 2000.
- [25] E. E. Swanson, J. Walton II and H. Heshmat, "A 35,000 RPM Test Rig for Magnetic, Hybrid and Back-up Bearings," in *ASME 1999 International Gas Turbine and Aeroengine Congress and Exhibition*, Iniana USA, 1999.
- [26] P. McMullen, V. Vuong and L. Hawkins, "Flywheel Energy Storage System with AMB's and Hybrid Backup Bearings," in *Proceedings of the 10th International Symposium on Magnetic Bearings*, 2006.
- [27] M. A. Fumagalli, "Modelling and Measurement Analysis of the Contact Interaction between a High Speed Rotor and its Stator," Swiss Institute of Technology, Zurich, 1997.
- [28] C. Jarroux, R. Dufour, J. Mahfoud, B. Defoy and T. Alban, "Parametric analysis of a rigid rotor drop onto touchdown bearings," in *M07 Colloque EUROMECH Coupling and Nonlinear interactions in Rotating Machinery*, 2015.
- [29] M. Helfert, M. Ernst, R. Nordmann and B. Aeschlimann, "High-speed video analysis of rotor-retainer-bearing-contacts due to failure of active magnetic bearings," in *10th international Symposium on Magnetic Bearings*, Martigny, 2006.
- [30] M. Agnieszka, Rotordynamics, CRC press, 2005.

-
- [31] L. Hawkins, A. Filatov, S. Umani and D. Prosser, "Test results and analytical predictions for rotor drop testing of an active magnetic bearing expander/generator," *Journal of engineering for gas turbines and power*, vol. 129, no. 2, pp. 522-529, 2007.
- [32] L. Hawkins, P. McMullen and V. Vuong, "Development and Testing of the Backup Bearing System for an AMB Energy Storage Flywheel," in *ASME Turbo Expo 2007: Power for Land, Sea and Air*, Motreal Canada, 2007.
- [33] J. Wilkes, J. Moore, D. Ransom and G. Vannini, "An Improved Catcher Bearing Model and an Explanation of the Forward Whirl/Whip Phenomenon Observed in Active Magnetic Bearing Transient Drop Experiments," *ASME Turbo Expo 2013: Turbine Technical Conference and Exposition*, pp. V07BT30A015--V07BT30A015, 2013.
- [34] M. Fumagalli and G. Schweitzer, "Impact dynamics of high-speed," in *Proceedings in the 4th International Symposium on Magnetic bearings*, Zurich, 1994.
- [35] P. McMullen and L. Hawkins, "Long Term Backup Bearing Testing Results".
- [36] A. Y. Kärkkäinen, M. Helfert, B. Aeschlimann, A. M. Mikkola and J. T. Sopenen, "Effect of Misalignment of Retainer Bearings on Dynamic Responses of Rotor System during Emergency Stop," in *ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Las Vegas, 2007.
- [37] A. Y. Kärkkäinen, J. T. Sopenen and A. . M. Mikkola, "Simulation of AMB Supported Rotor During Drop on Retainer Bearings," Lappeenranta Finland, 2006.
- [38] R. M. Miller, *Backup bearings for extreme speed touch down applications*, Google Patents, 1996.
- [39] API Standard, "617, 2014," *Axial and Centrifugal Compressors and Expander-Compressors for Petroleum, Chemical and Gas Industry Services,* Eighth Edition, American Petroleum Institute, Washington, DC, 2014.
- [40] FAG - Schaeffler Group, "Rolling Bearing Damage," December 2010. [Online]. Available: http://www.schaeffler.com/remotemedien/media/_shared_media/08_media_library/01_publications/schaeffler_2/publication/downloads_18/wl_82102_3_de_en.pdf. [Accessed 30 March 2016].
- [41] Torrington, "Bearing Failure Prevention Guide," [Online]. Available: <https://www.applied.com/static/catalog/pdfs/bearingfailure.pdf>. [Accessed 2 March 2016].
- [42] The Barden Corporation, "Bearing Failure: Causes and cures," April 2007. [Online]. Available: http://www.schaeffler.com/remotemedien/media/_shared_media/08_media_library/01_publications/barden/brochure_2/downloads_24/barden_bearing_failures_us_en.pdf. [Accessed 5 March 2016].
- [43] Timken, "Bearing Damage Analysis," [Online]. Available: <http://www.timken.com/EN-US/products/maintdiag/Documents/5892-Timken-Bearing-Damage-Analysis-with-Lubrication->

Reference-Guide.pdf. [Accessed 4 March 2016].

- [44] MEGGITT, "Bearing Failure: Causes and Cures," [Online]. Available: <http://www.wilcoxon.com/knowdesk/bearing.pdf>. [Accessed 1 March 2016].
- [45] R. D. Evans, "Classing Bearing Damage Modes," in *Wind Turbine Tribology Seminar*, Broomfield, CO, USA, 2011.
- [46] E. Ioannides and T. Harris, "A new fatigue life model for rolling bearings," *Journal of Tribology*, vol. 107, no. 3, pp. 367-377, 1985.
- [47] R. M. Barnsby, Life ratings for modern rolling bearings: a design guide for the application of International Standard ISO 281/2, vol. 1, American Society of Mechanical Engineers, 2003.
- [48] G. Sun, "Auxiliary Bearing Life Prediction Using Hertzian Contact Bearing Model," *Journal of Vibration and Acoustics*, vol. 128, no. 2, pp. 203 - 209, 9 September 2005.
- [49] J. M. Gouws, J. J. Janse van Rensburg and C. Vanek, "Backup-Bearing lifetime prediction using quantified delevitation severity indicators," in *Proceedings of the 10th Workshop on Magnetic Bearings Technology*, Zittau Germany, 2015.

Appendix A. Calculation examples

A1. Full Delevitation

The equation of $DVAL$ $VVAL$ and $AVVAL$ is given by

$$DVAL(k) = \sum_i^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap}} \quad (A1)$$

$$VVAL(k) = \sum_i^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap} (t(i) - t)} \quad (A2)$$

$$VVAL(k) = \sum_i^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap} \cdot (t(i) - t)^2} \quad (A3)$$

An example for calculating delevitation severity for a full delevitation is based on the first RDE of a bearing subjected to multiple 4000 r/min delevitations until failure occurred. The list below shows the variables recorded during the specified rotor speeds (4000 – 0 r/min).

- Index number at 2500 r/min, $i = 275767$
- Index number at 1000 r/min, $k = 636278$
- Time at index number i , $t = 27.5767$ s
- Time at index number k , $t(i) = 63.6278$ s
- Airgap radius, $(r_{airgap}) = 200 \mu\text{m}$

Substituting the above variables into equation (A1)-(A3) yields

$$DVAL(876925) = \sum_1^{876925} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6})}$$

$$VVAL(876925) = \sum_1^{876925} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (87.6925 - 0)}$$

$$AVVAL(876925) = \sum_1^{876925} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (87.6925 - 0)^2}$$

- **For $i = 2$**

- $x_1 = 1.8261e^{-5}$ mm
- $x_2 = 1.578e^{-5}$ mm
- $y_1 = -4.2314e^{-6}$ mm

- $y_2 = -1.1053e^{-6}$ mm
- $t = 0.00009912$ s

$$DVAL(2) = \frac{\sqrt{\left((1.578e^{-5}) - (1.8261e^{-5})\right)^2 + \left((-1.1053e^{-6}) - (-4.2314e^{-6})\right)^2}}{200 \times 10^{-6}}$$

$$= 0.0363 \text{ times}$$

$$VVAL(2) = \frac{DVAL(2)}{(0.00009912 - 0)}$$

$$= 366.222 \text{ s}^{-1}$$

$$AVVAL(2) = \frac{DVAL(2)}{(0.00009912 - 0)^2}$$

$$= 3.6947 \times 10^6 \text{ s}^{-2}$$

- **For i = 3**

- $x_3 = 1.578e^{-5}$ mm
- $x_2 = 1.33e^{-5}$ mm
- $y_3 = -1.1053e^{-6}$ mm
- $y_2 = -1.17874e^{-6}$ mm
- $t = 0.00019912$ s

$$DVAL(3) = 0.0363 + \frac{\sqrt{\left((1.33e^{-5}) - (1.578e^{-5})\right)^2 + \left((-1.17874e^{-6}) - (-1.1053e^{-6})\right)^2}}{200 \times 10^{-6}}$$

$$= 0.07258 \text{ times}$$

$$VVAL(3) = \frac{DVAL(3)}{(0.00019912 - 0)}$$

$$= 364.5038 \text{ s}^{-1}$$

$$AVVAL(3) = \frac{DVAL(3)}{0.00019912^2}$$

$$= 1.8306 \times 10^6 \text{ s}^{-2}$$

·
·
·

- **For i = k (846842)**

$$DVAL(k) = DVAL(1) + DVAL(2) + ... + \frac{\sqrt{(x_{846842} - x_{846842-1})^2 + (y_{846842} - y_{846842-1})^2}}{200 \times 10^{-6}}$$

$$= 10930 \text{ times}$$

$$VVAL(k) = \frac{DVAL(k)}{(84.6842 - 0)}$$

$$= 129.0678 \text{ s}^{-1}$$

$$AVVAL(k) = \frac{DVAL(k)}{(84.6842 - 0)^2}$$

$$= 1.5241 \text{ s}^{-2}$$

A2. Bouncing and whirling

An example for calculating deleivation severity according to the most severe rotordynamic motion is based on the first RDE of a bearing subjected to multiple 4000 r/min deleivations until failure occurred. The list below shows the variables recorded during the specified rotordynamic motion.

- Index number at 4000 r/min, $(i) = 1$
- Index number at 2500 r/min, $(k) = 275767$
- Time at index number i , $t = 0 \text{ s}$
- Time at index number k , $t(i) = 27.5767 \text{ s}$
- Airgap radius, $(r_{airgap}) = 200 \text{ }\mu\text{m}$
- x- and y-position of rotor during deleivation can be found in appendix E

Substituting the above variables into equation (A1)-(A3) yields

$$DVAL(275767) = \sum_1^{275767} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{200 \times 10^{-6}}$$

$$VVAL(275767) = \sum_1^{275767} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (27.5767 - 0)}$$

$$AVVAL(275767) = \sum_1^{275767} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (27.5767 - 0)^2}$$

• **For i = 2**

- $x_1 = 1.8261e^{-5}$ mm
- $x_2 = 1.578e^{-5}$ mm
- $y_1 = -4.2314e^{-6}$ mm
- $y_2 = -1.1053e^{-6}$ mm
- $t = 0.00009912$ s

$$DVAL(2) = \frac{\sqrt{((1.578e^{-5}) - (1.8261e^{-5}))^2 + ((-1.1053e^{-6}) - (-4.2314e^{-6}))^2}}{200 \times 10^{-6}}$$

$$= 0.0363 \text{ times}$$

$$VVAL(2) = \frac{DVAL(2)}{(0.00009912 - 0)}$$

$$= 366.222 \text{ s}^{-1}$$

$$AVVAL(2) = \frac{DVAL(2)}{(0.00009912 - 0)^2}$$

$$= 3.6947 \times 10^6 \text{ s}^{-2}$$

• **For i = 3**

- $x_3 = 1.578e^{-5}$ mm
- $x_2 = 1.33e^{-5}$ mm
- $y_3 = -1.1053e^{-6}$ mm
- $y_2 = -1.17874e^{-6}$ mm
- $t = 0.00019912$ s

$$DVAL(3) = 0.0363 + \frac{\sqrt{((1.33e^{-5}) - (1.578e^{-5}))^2 + ((-1.17874e^{-6}) - (-1.1053e^{-6}))^2}}{200 \times 10^{-6}}$$

$$= 0.07258 \text{ times}$$

$$VVAL(3) = \frac{DVAL(3)}{(0.00019912 - 0)}$$

$$= 364.5038 \text{ s}^{-1}$$

$$AVVAL(3) = \frac{DVAL(3)}{0.00019912^2}$$

$$= 1.8306 \times 10^6 s^{-2}$$

.

.

.

.For i = k (275400)

- $x_k = 7.6552e^{-5}$ mm
- $x_{k-1} = 7.7172e^{-5}$ mm
- $y_k = -1.8407e^{-4}$ mm
- $y_{k-1} = -1.8345e^{-4}$ mm
- $t @ k = 27.5400$ s

$$DVAL(k) = DVAL(1) + DVAL(2) + ... + \frac{\sqrt{(x_{275400} - x_{275400-1})^2 + (y_{275400} - y_{275400-1})^2}}{200 \times 10^{-6}}$$

$$= 5860 \text{ times}$$

$$VVAL(k) = \frac{DVAL(k)}{(27.513 - 0)}$$

$$= 212.99 s^{-1}$$

$$AVVAL(k) = \frac{DVAL(k)}{(27.513 - 0)^2}$$

$$= 7.7414 s^{-2}$$

A3. Oscillation

For case B, life analysis is done during the period when an oscillating motion is present (2500 – 1000 r/min). This example is based on the first RDE of a bearing subjected to 142 RDEs until failure. The list below shows the variables recorded during the specified rotordynamic motion.

- Index number at 2500 r/min, $i = 275767$
- Index number at 1000 r/min, $k = 636278$
- Time at index number i , $t = 27.5767$ s
- Time at index number k , $t(i) = 63.6278$ s
- Airgap radius, $(r_{airgap}) = 200 \mu\text{m}$
- x - and y -position of rotor during delevitation can be found in appendix E

Substituting the above variables into equation (A1)-(A3) yields

$$DVAL(636278) = \sum_{275767}^{636278} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{200 \times 10^{-6}}$$

$$VVAL(636278) = \sum_{275767}^{636278} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (63.6278 - 27.5767)}$$

$$AVVAL(636278) = \sum_{275767}^{636278} \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{(200 \times 10^{-6}) \cdot (63.6278 - 27.5767)^2}$$

For i = 275767

- $x_{275767} = -6.2354e^{-5}$ mm
- $x_{275767-1} = -6.4835e^{-5}$ mm
- $y_{275767} = -1.7476e^{-4}$ mm
- $y_{275767-1} = -1.7476e^{-4}$ mm
- $t(275767) = 27.5767$ s
- $t = 27.5766$ s

$$DVAL(275768) = \frac{\sqrt{((-6.2354e^{-5}) - (-6.4835e^{-5}))^2 + ((-1.7476e^{-6}) - (-1.7476e^{-6}))^2}}{200 \times 10^{-6}}$$

$$= 0.0124 \text{ times}$$

$$\begin{aligned} \cdot VVAL(275767) &= \frac{DVAL(275767)}{(27.5767 - 27.5766)} \\ &= 124 \text{ s}^{-1} \end{aligned}$$

$$\begin{aligned} AVVAL(275767) &= \frac{DVAL(275767)}{(27.5767 - 27.5766)^2} \\ &= 1.24 \times 10^6 \text{ s}^{-2} \end{aligned}$$

For i = 275768

- $x_{275768} = -6.0494e^{-5}$ mm
- $x_{275767} = -6.2354e^{-5}$ mm
- $y_{275768} = -1.7538e^{-4}$ mm
- $y_{275767-1} = -1.7476e^{-4}$ mm
- $t(275768) = 27.5768$ s
- $t = 27.5766$ s

$$DVAL(275768) = DVAL(275767) + \frac{\sqrt{((-6.0494e^{-5}) - (-6.2354e^{-5}))^2 + ((-1.7538e^{-6}) - (-1.7476e^{-6}))^2}}{200 \times 10^{-6}}$$

$$= 0.0124 + 0.0099$$

$$= 0.0223 \text{ times}$$

$$\begin{aligned} \cdot VVAL(275768) &= \frac{DVAL(275768)}{(27.5768 - 27.5766)} \\ &= 111.5 \text{ s}^{-1} \end{aligned}$$

$$\begin{aligned} AVVAL(275768) &= \frac{DVAL(275768)}{(27.5768 - 27.5766)^2} \\ &= 5.575 \times 10^5 \text{ s}^{-2} \end{aligned}$$

•
•

• **For i = k (636278)**

- $x_k = 7.6552e^{-5} \text{ mm}$
- $x_{k-1} = 7.7172e^{-5} \text{ mm}$
- $y_k = -1.8407e^{-4} \text{ mm}$
- $y_{k-1} = -1.8345e^{-4} \text{ mm}$
- $t(k) = 63.6278 \text{ s}$
- $t = 27.5766 \text{ s}$

$$DVAL(k) = DVAL(275767) + DVAL(275768) + \dots + \frac{\sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2}}{200 \times 10^{-6}}$$

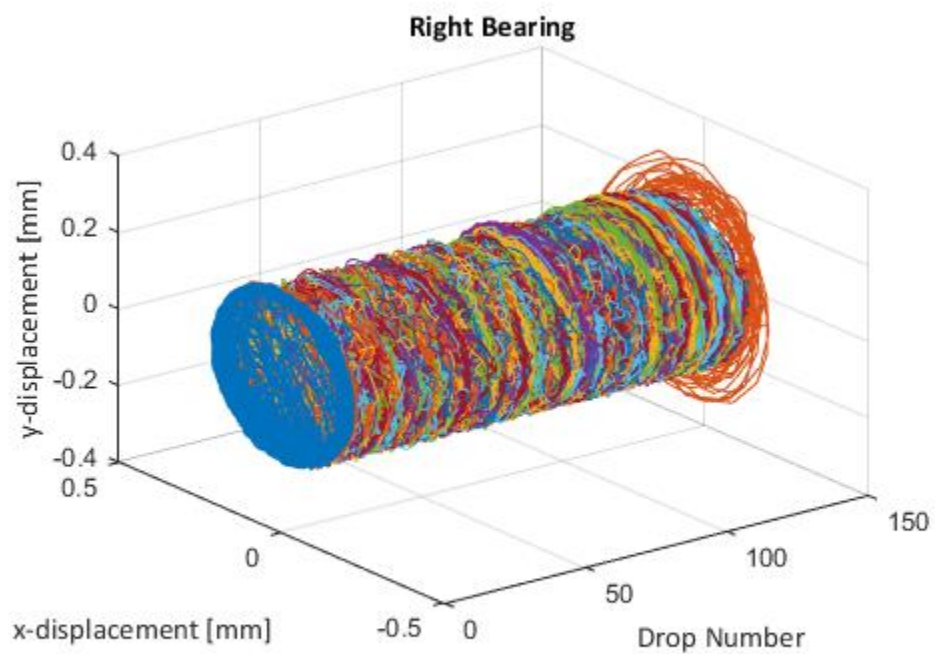
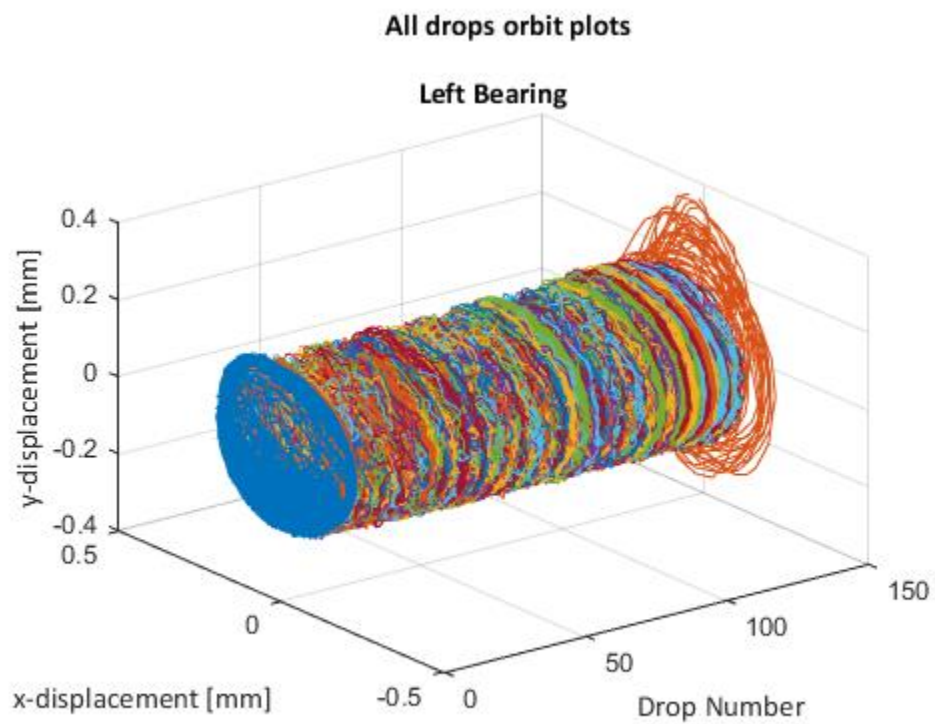
$$= 3718.3 \text{ times}$$

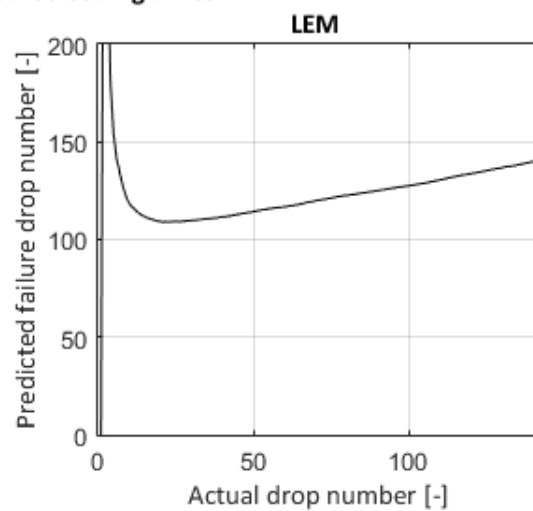
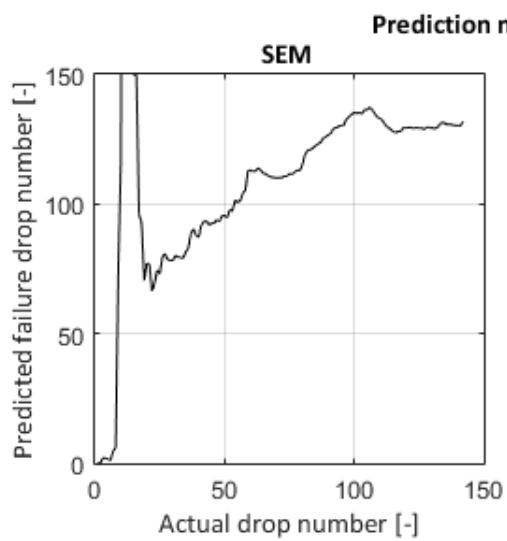
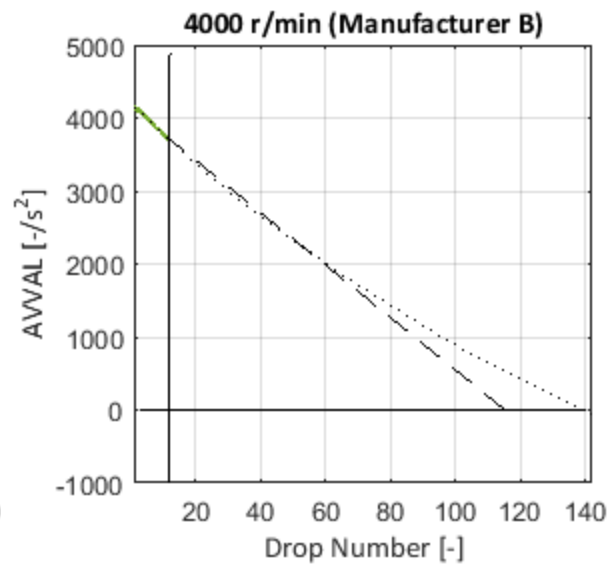
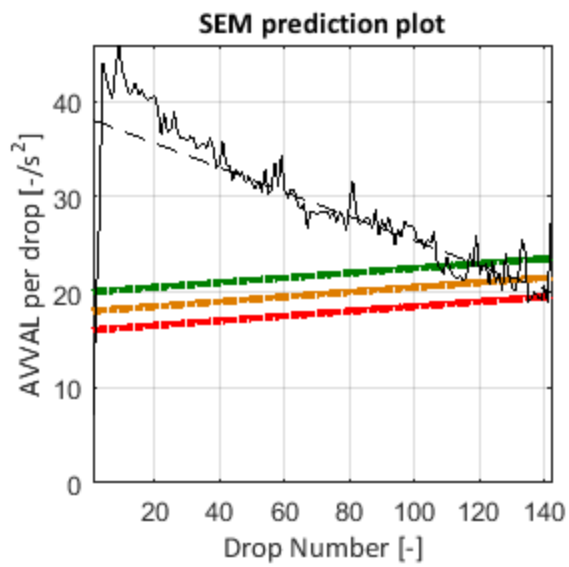
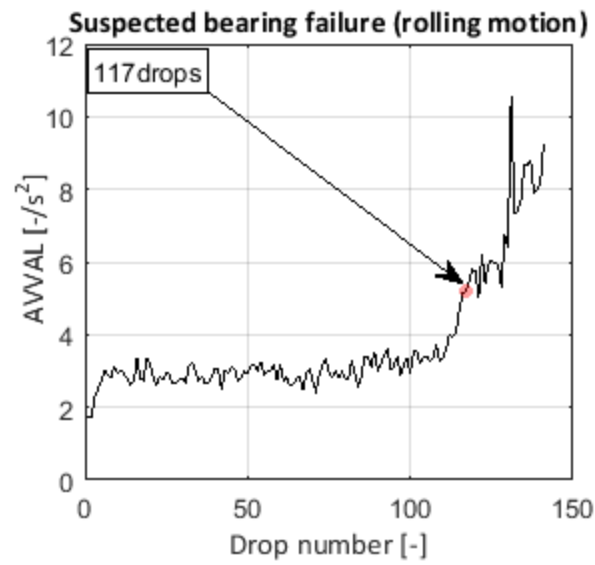
$$\begin{aligned} VVAL(k) &= \frac{DVAL(k)}{(63.6278 - 27.54)} \\ &= 103.24 \text{ s}^{-1} \end{aligned}$$

$$\begin{aligned} AVVAL(k) &= \frac{DVAL(k)}{(63.6278 - 27.54)^2} \\ &= 2.8665 \text{ s}^{-2} \end{aligned}$$

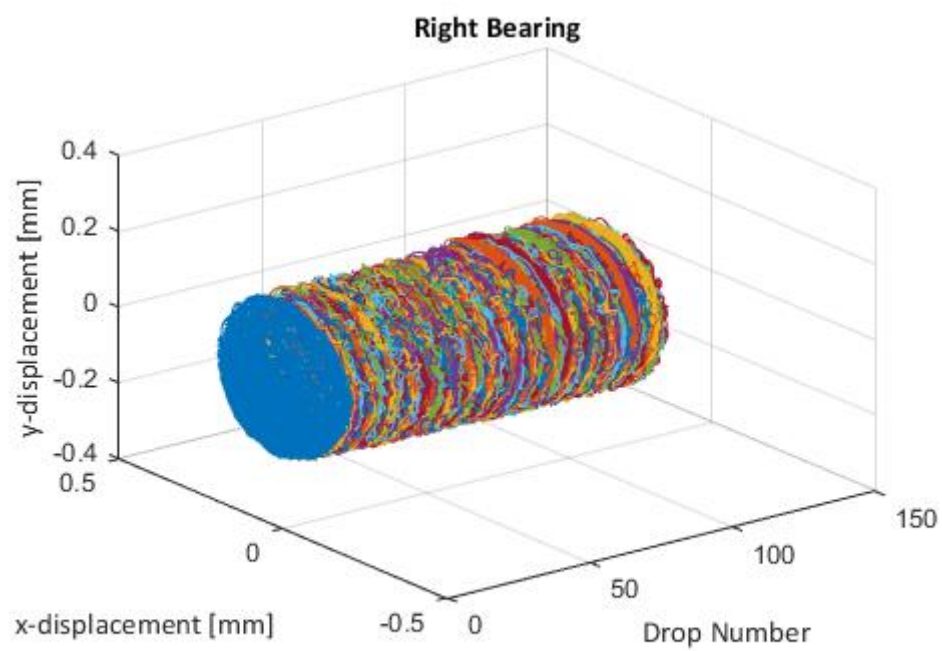
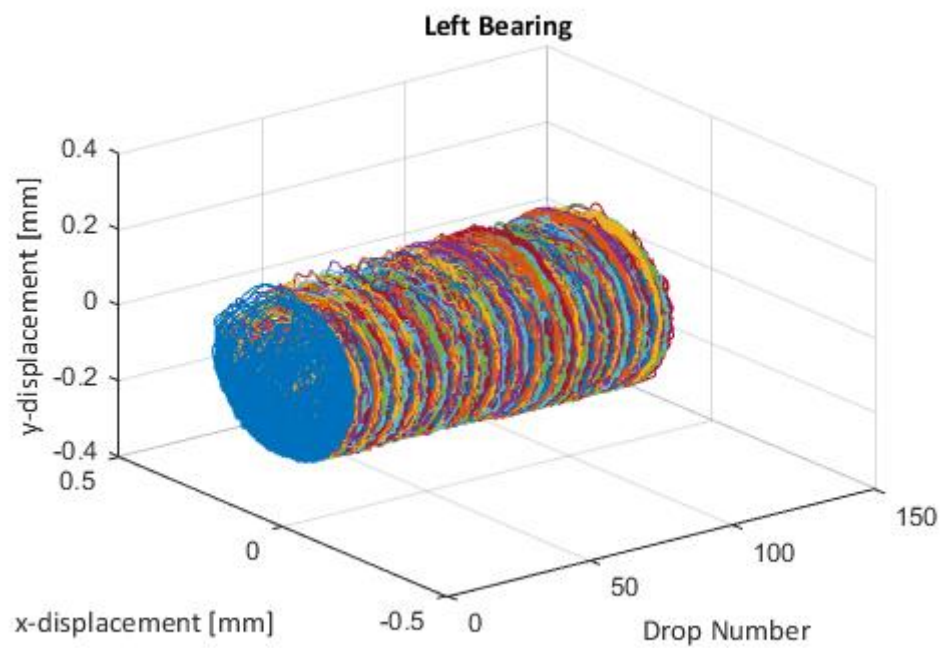
Appendix B. Rotor delevitation results

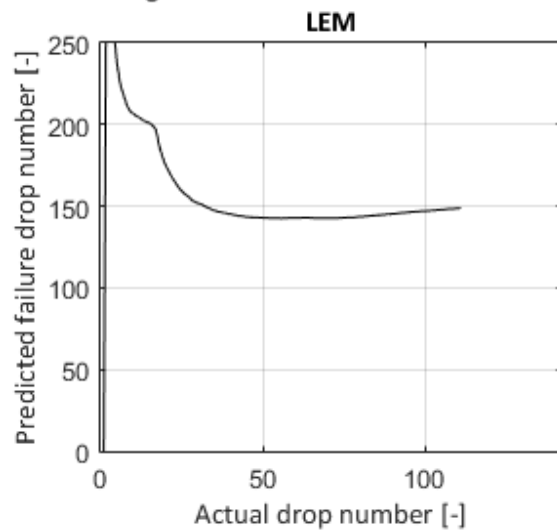
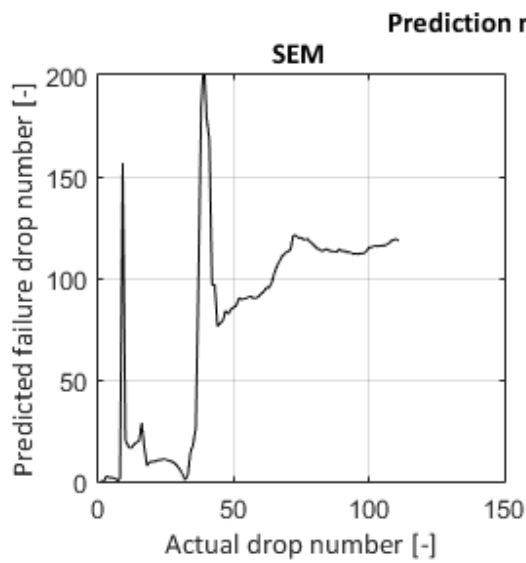
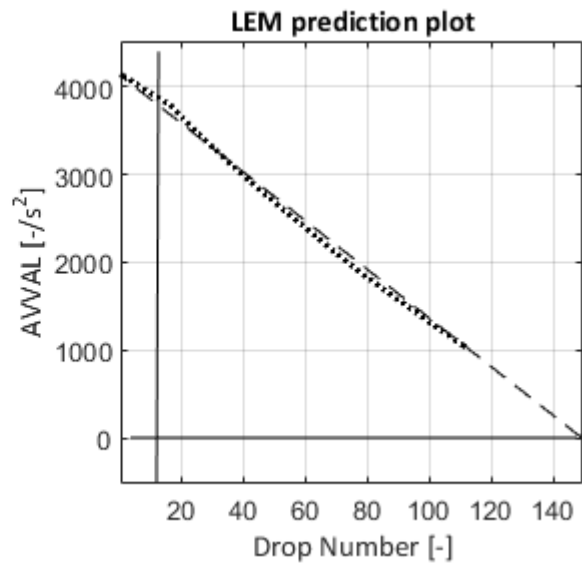
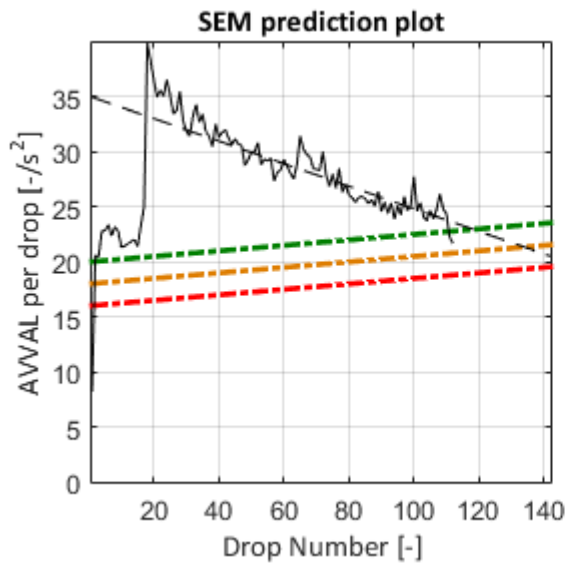
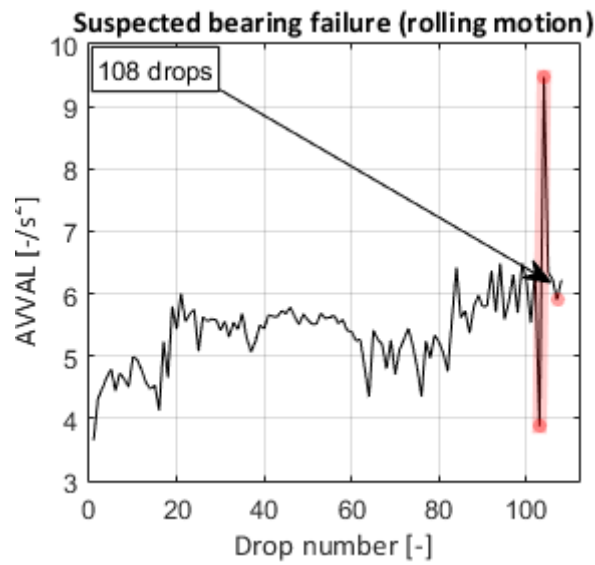
B1. 4000 r/min drop results: Bearing set 1



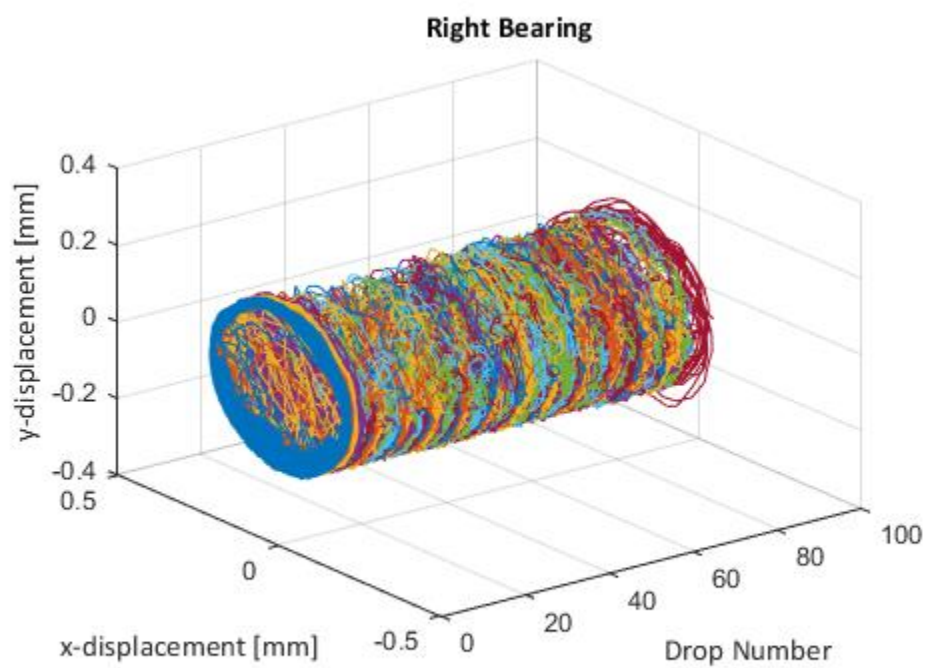
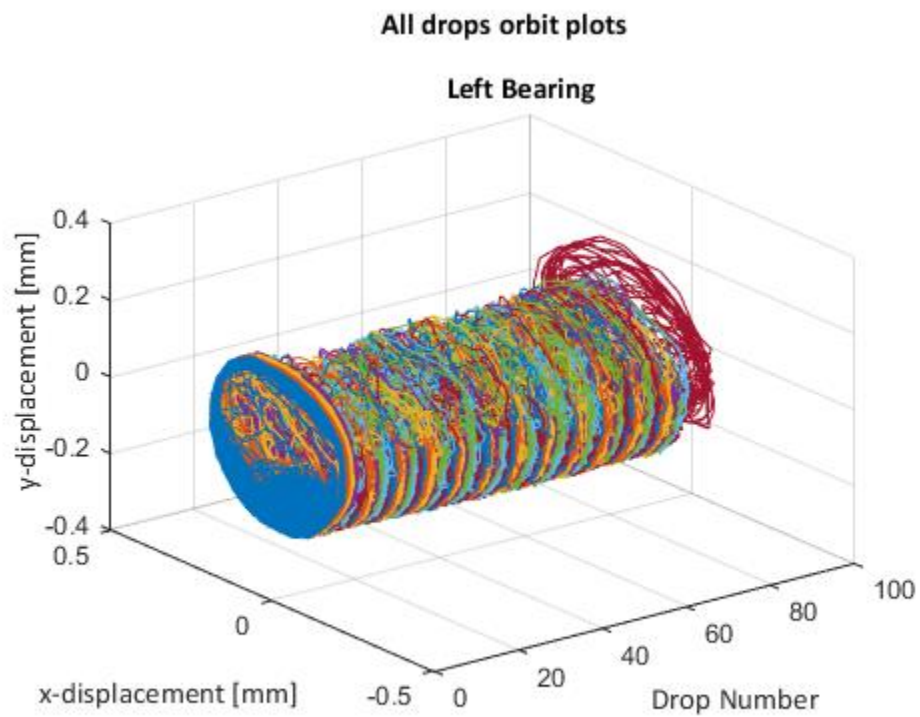


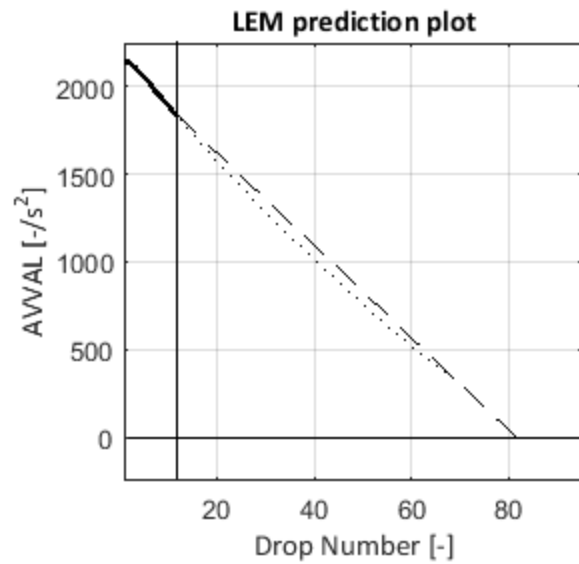
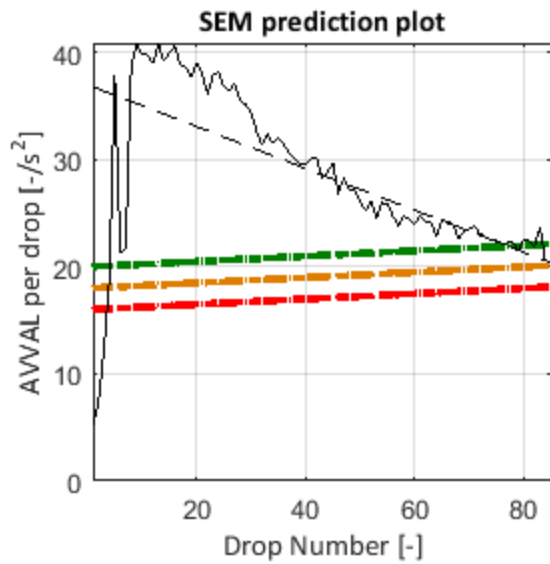
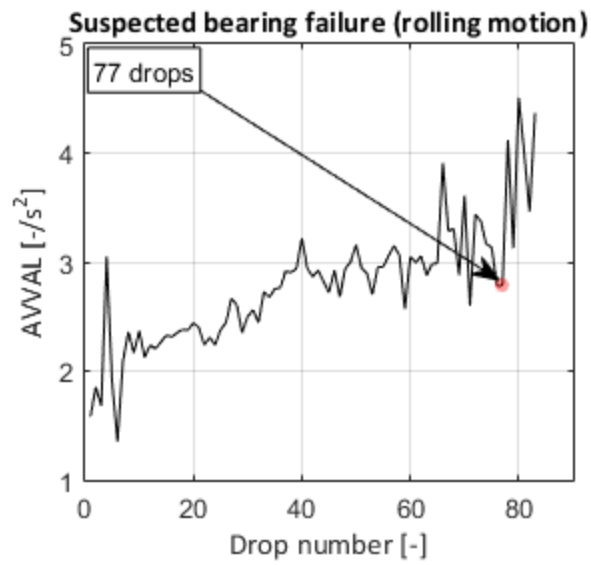
B2. 4000 r/min drop results: Bearing set 2



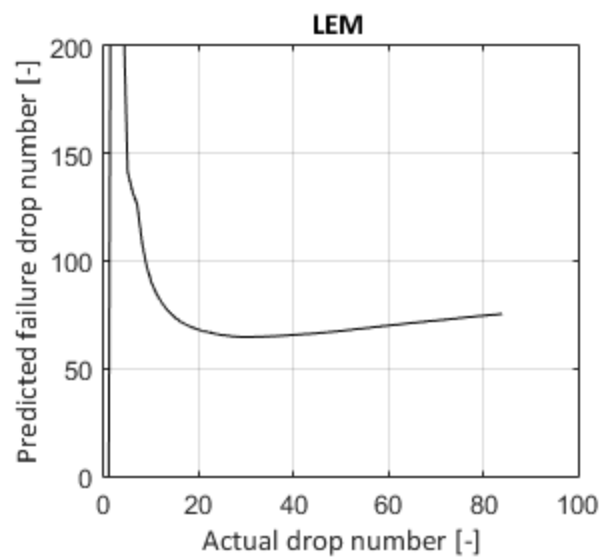
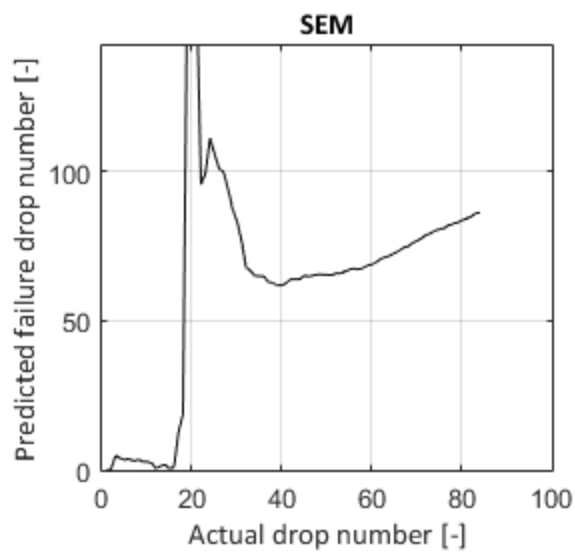


B3. 4500 r/min drop results: Bearing set 1

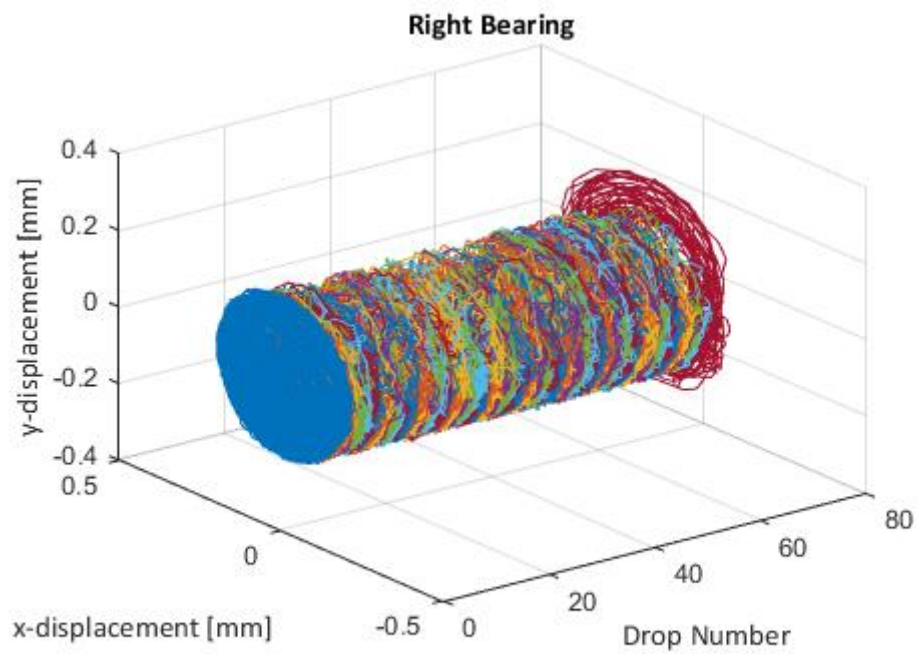
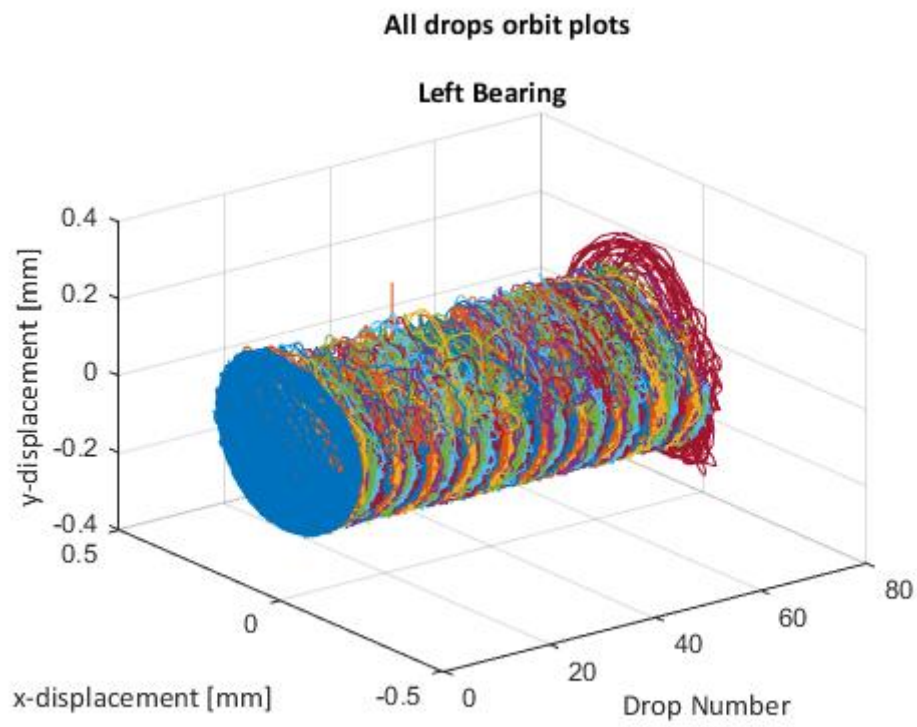


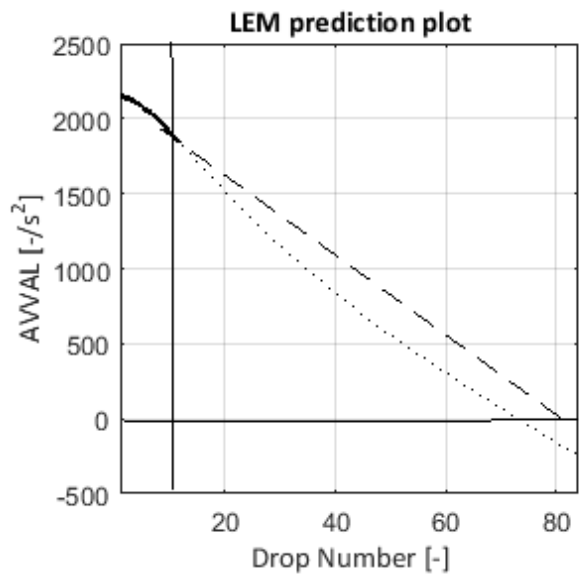
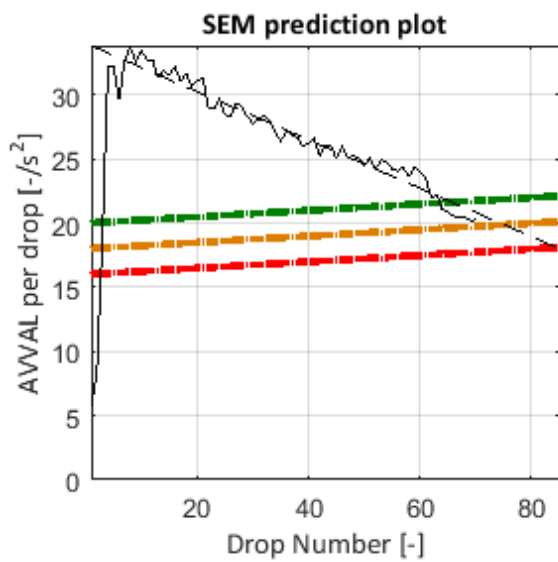
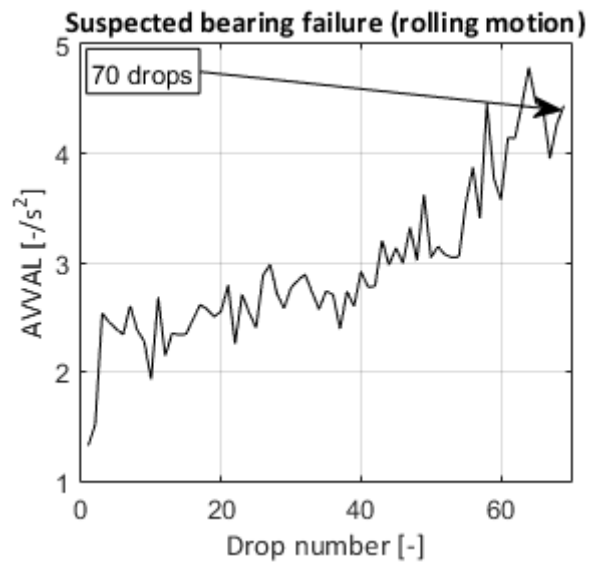


Prediction method settling times

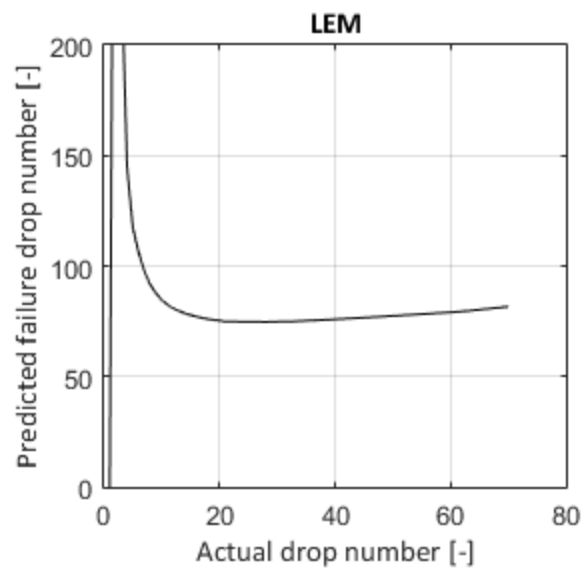
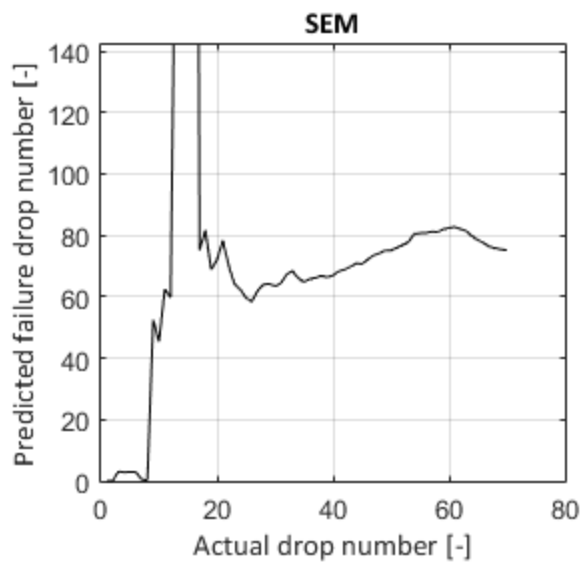


B4. 4500 r/min drop results: Bearing set 2

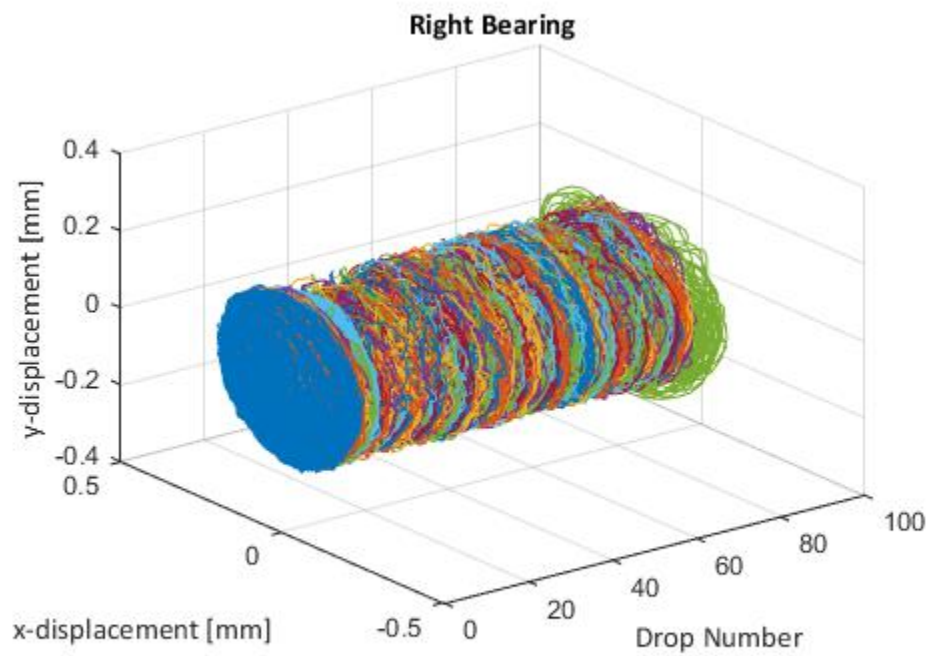
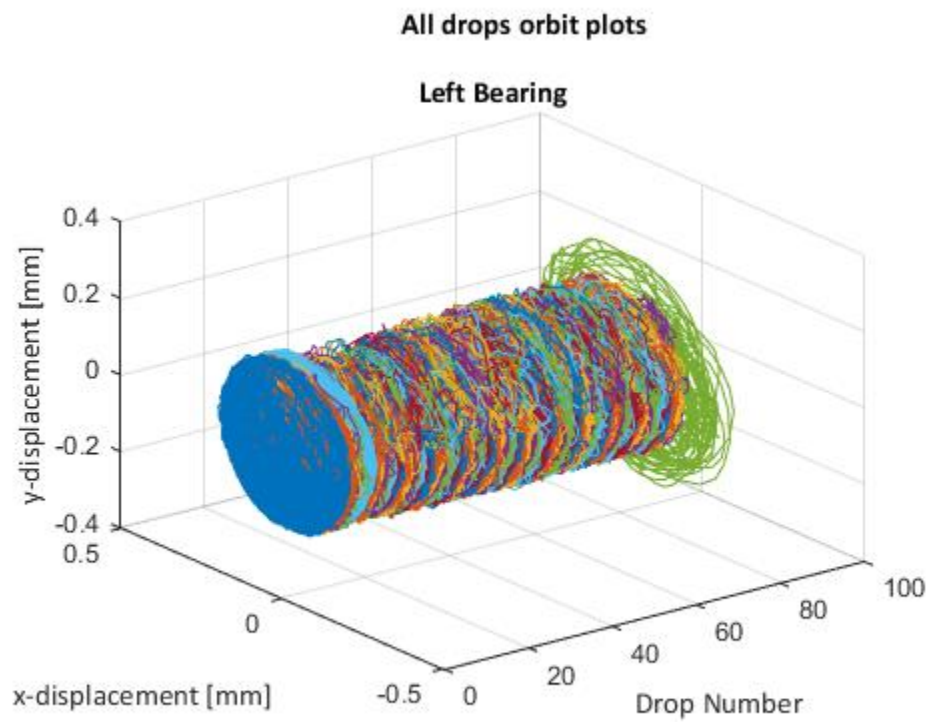


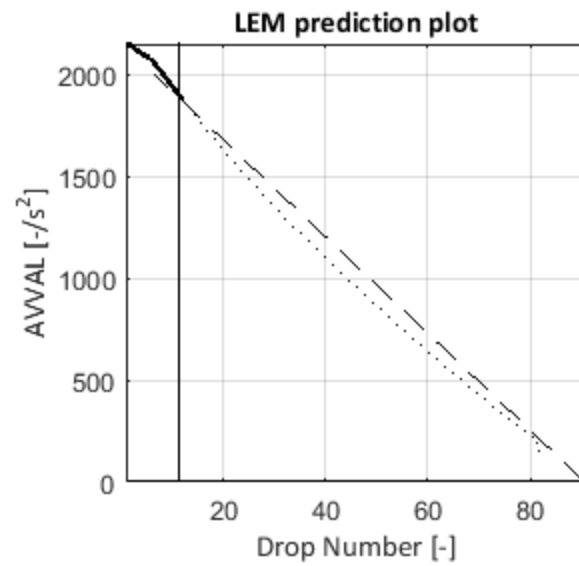
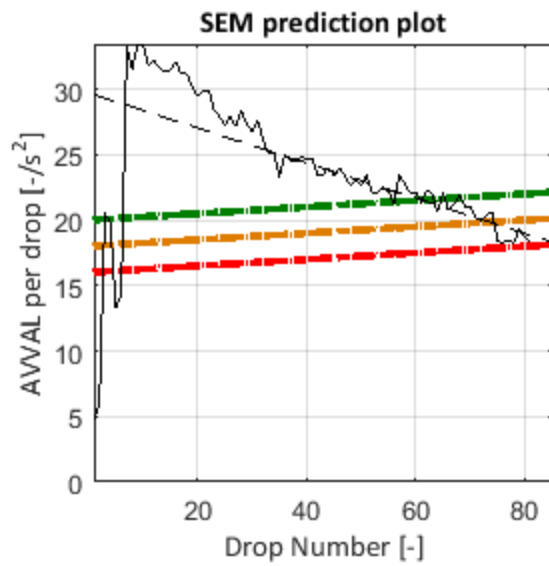
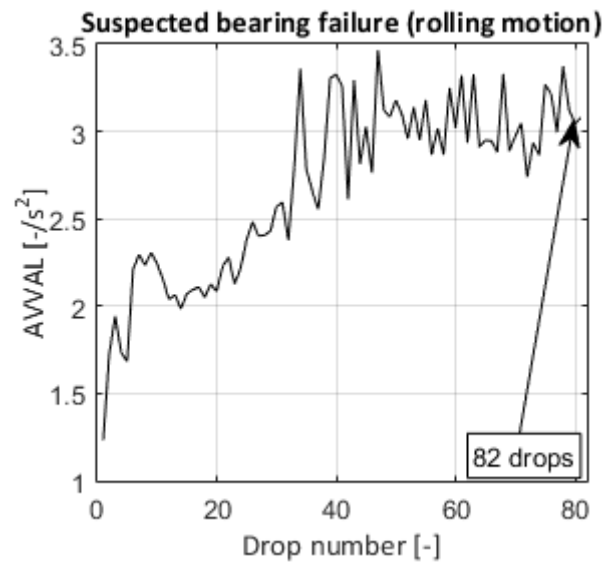


Prediction method settling time

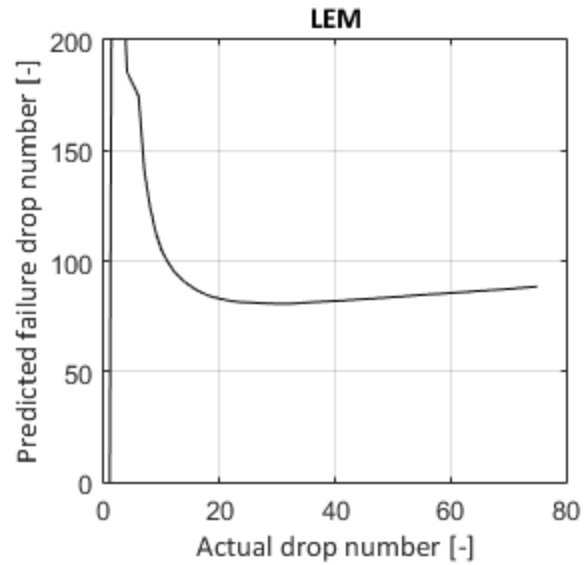
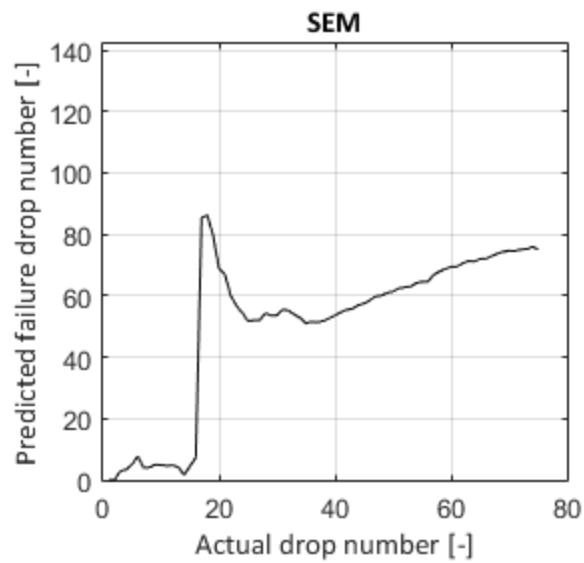


B5. 4500 r/min drop results: Bearing set 3

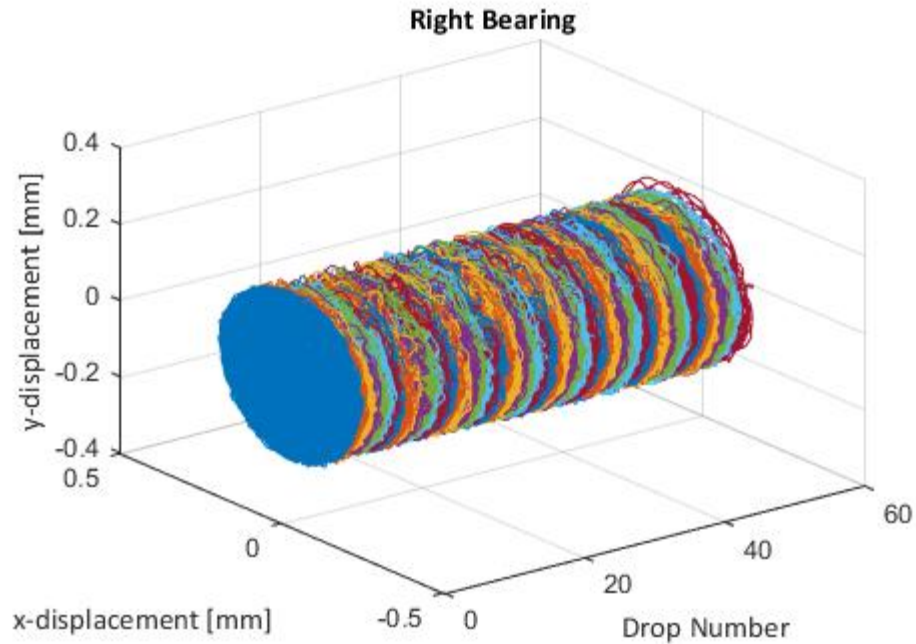
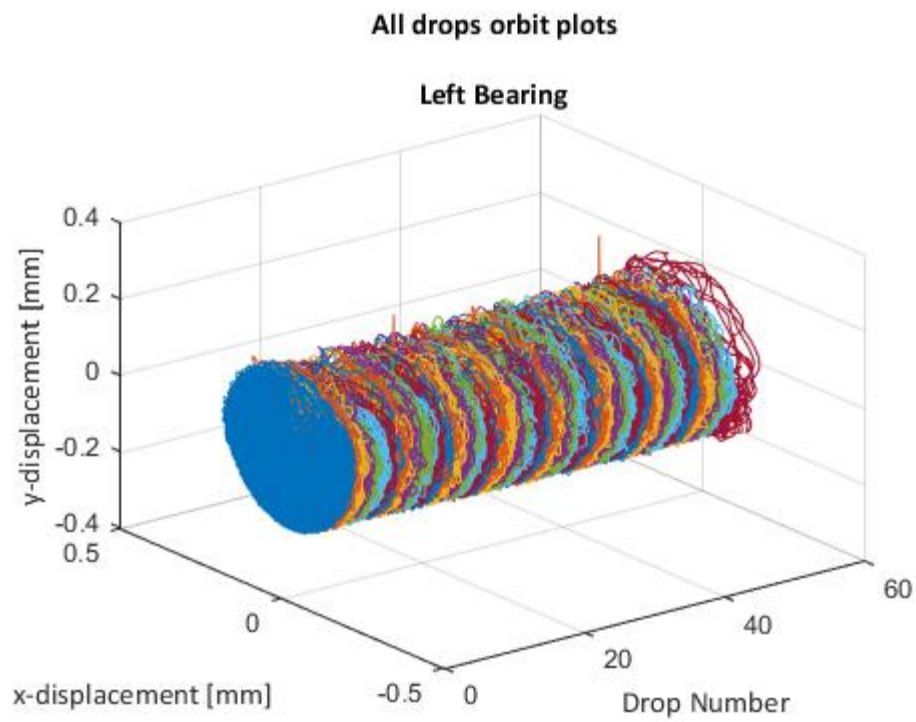


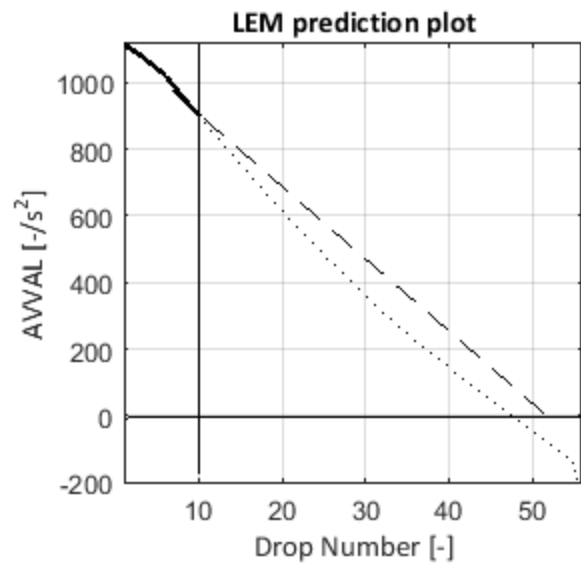
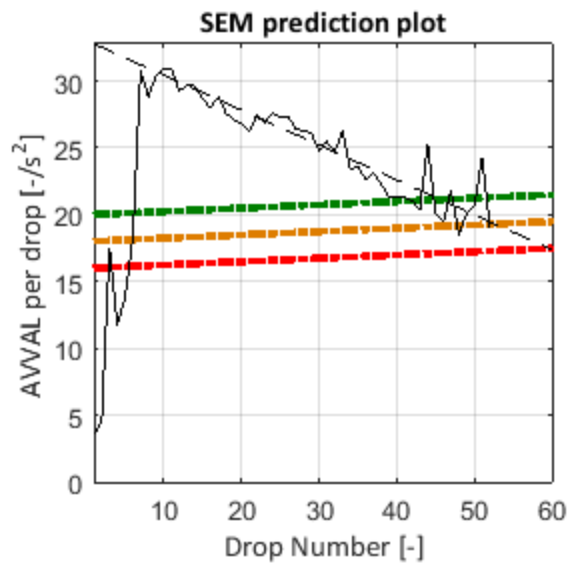
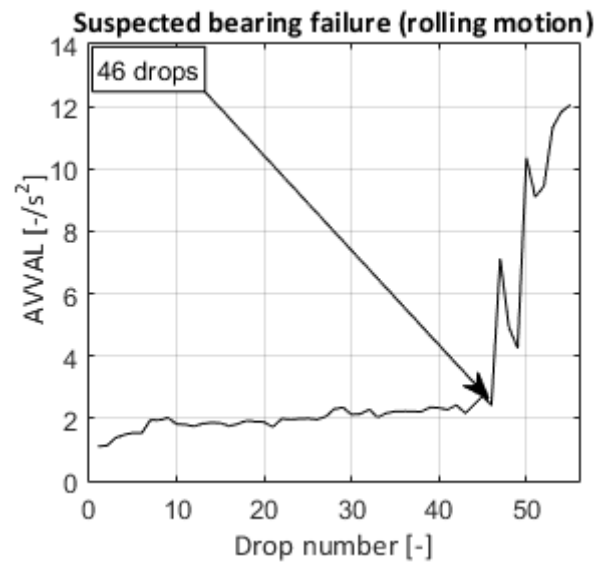


Prediction method settling time

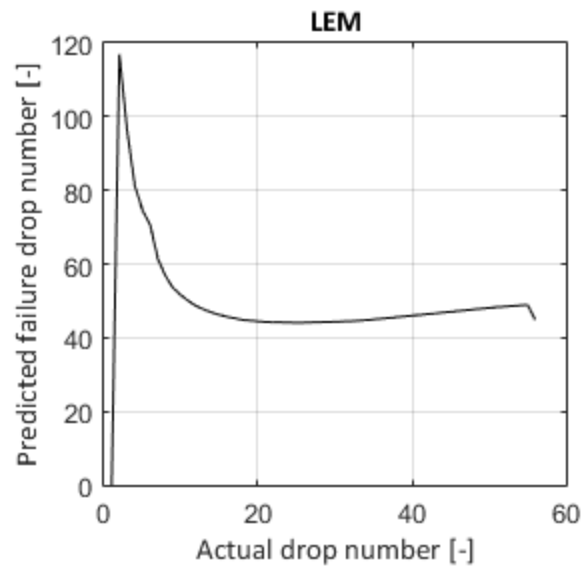
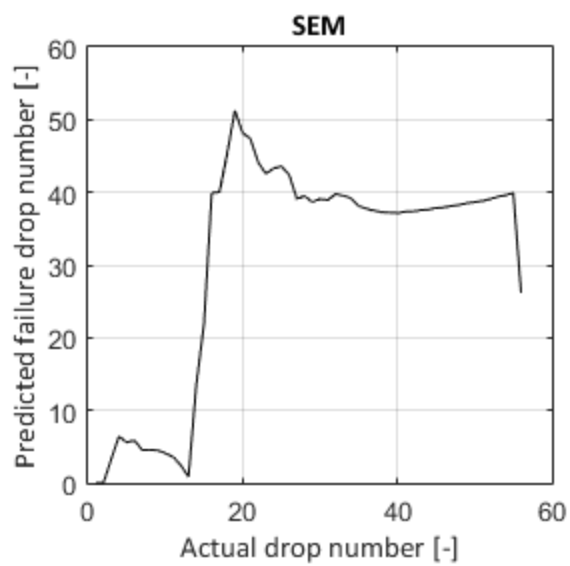


B6. 5000 r/min drop results: Bearing set 1

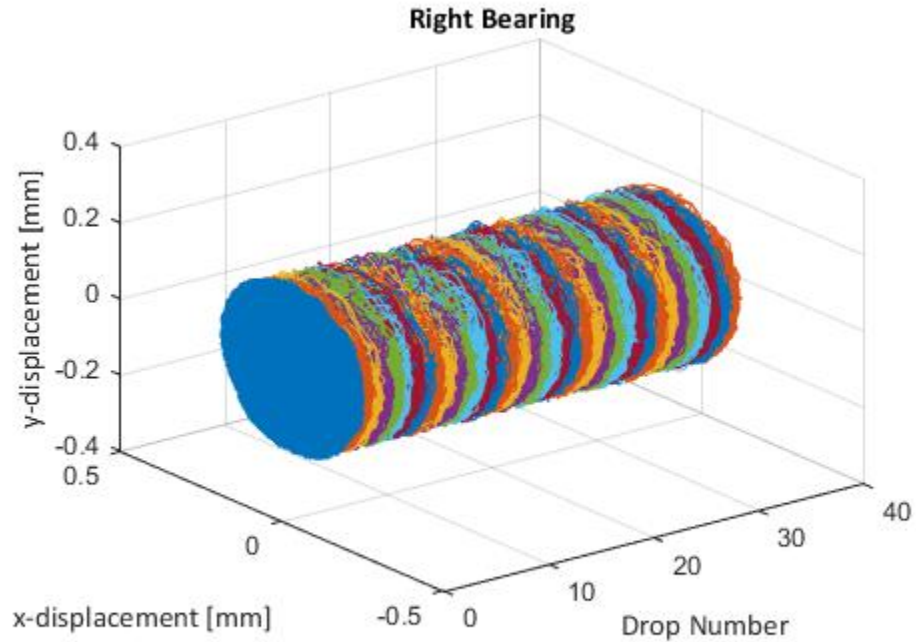
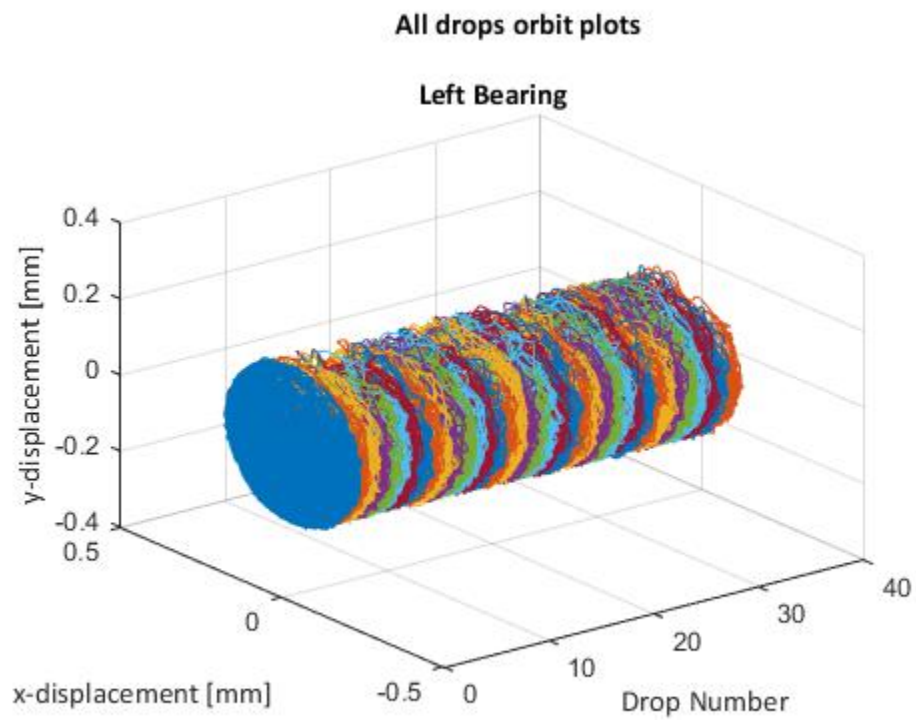


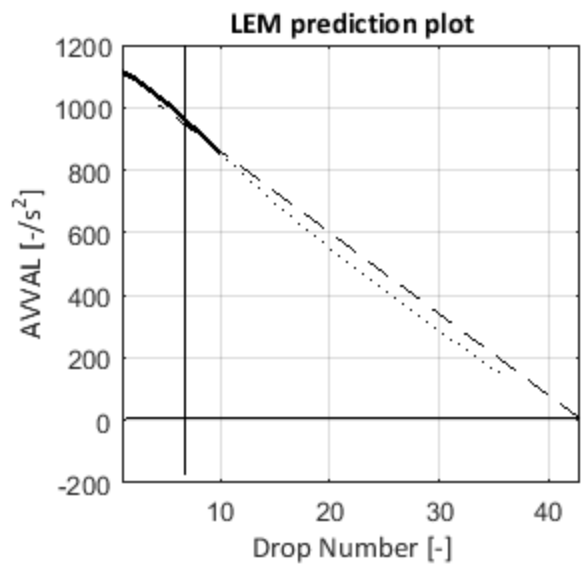
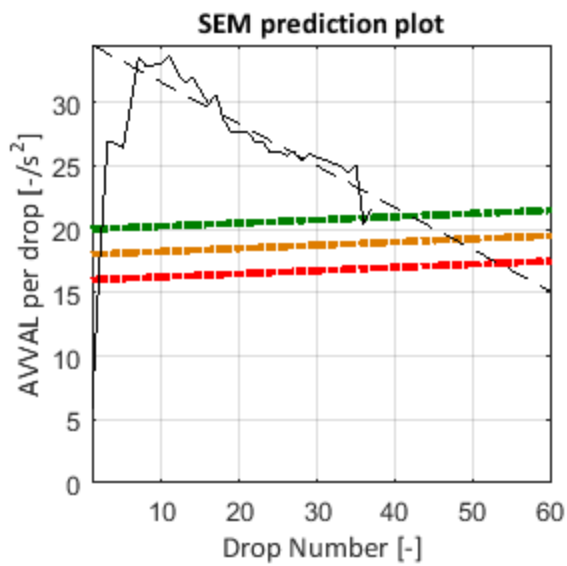
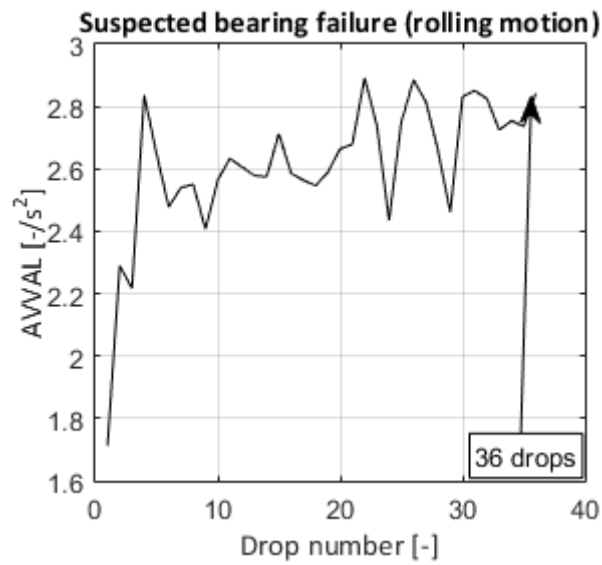


Prediction method settling time

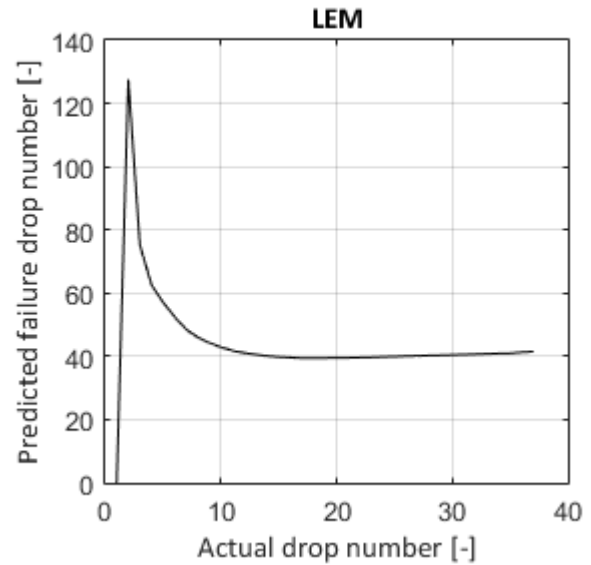
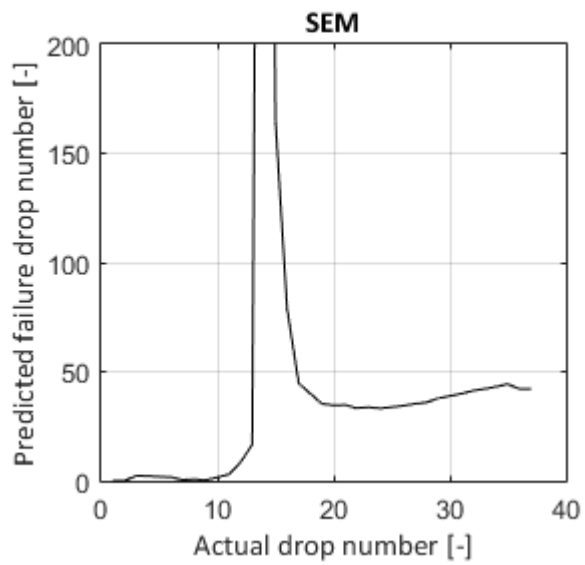


B7. 5000 r/min drop results: Bearing set 2

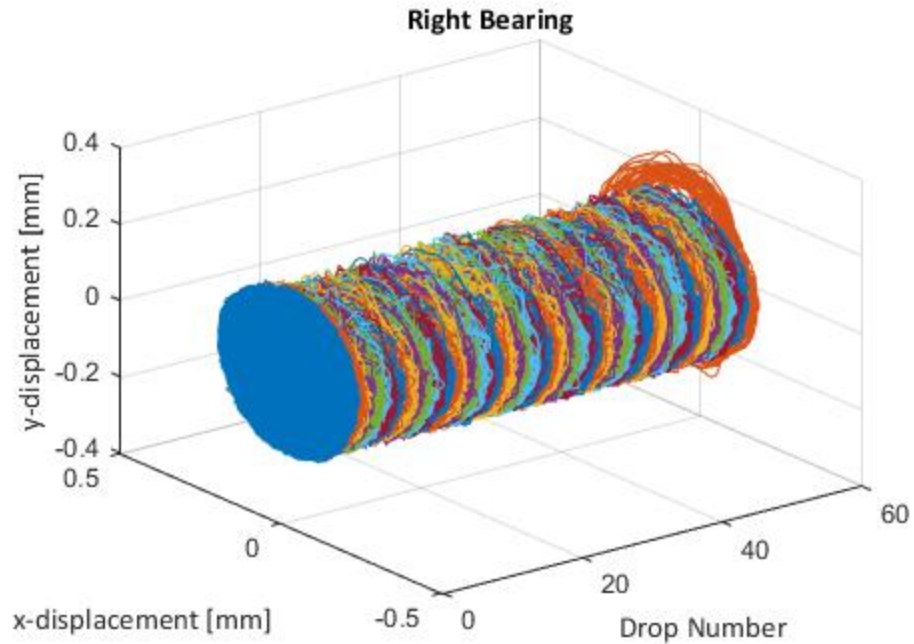
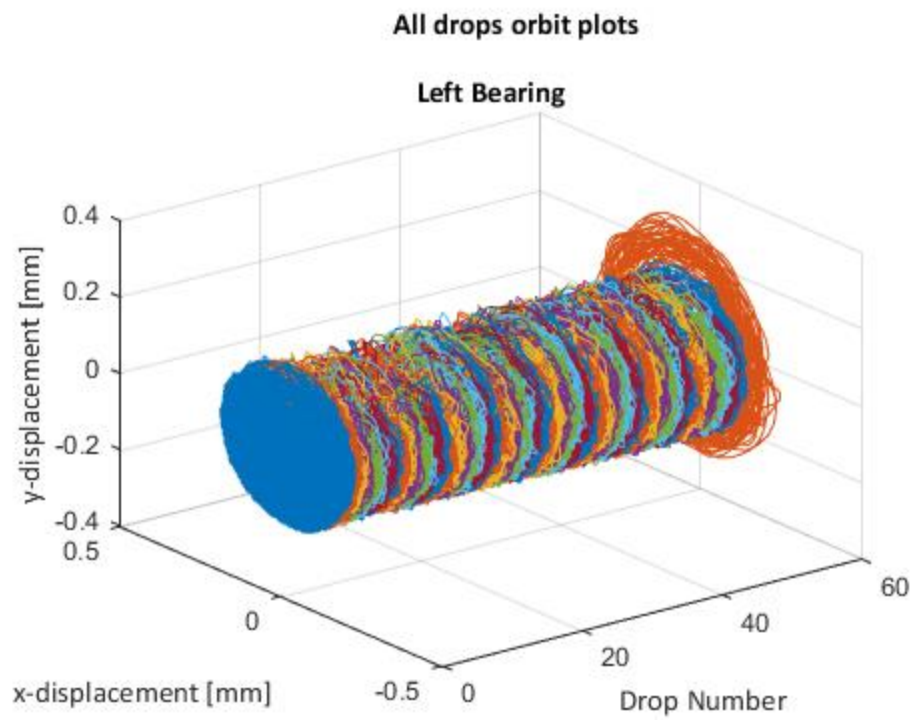


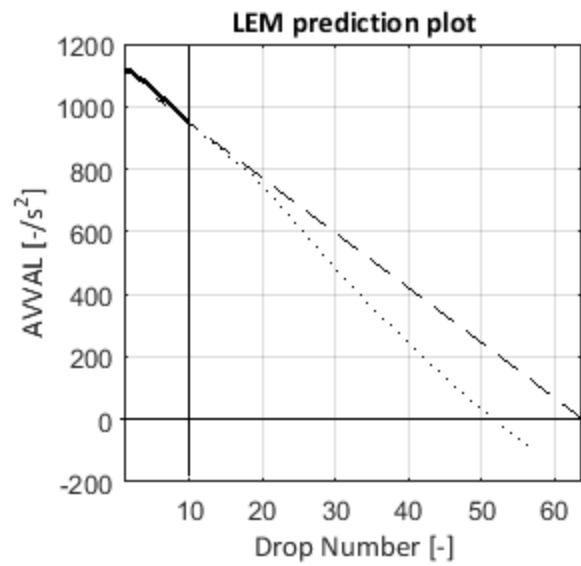
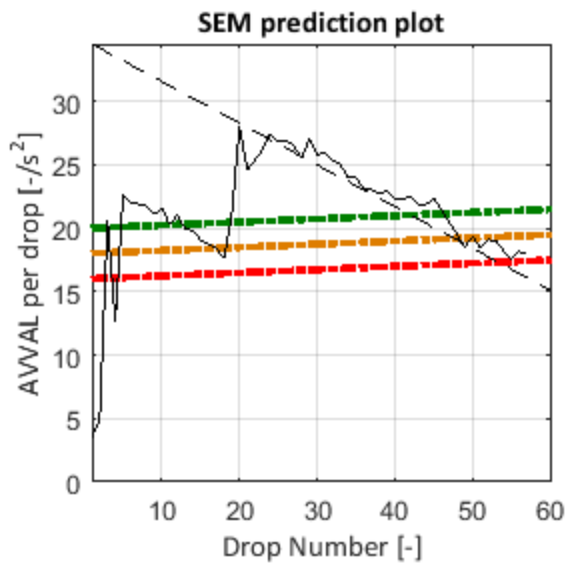
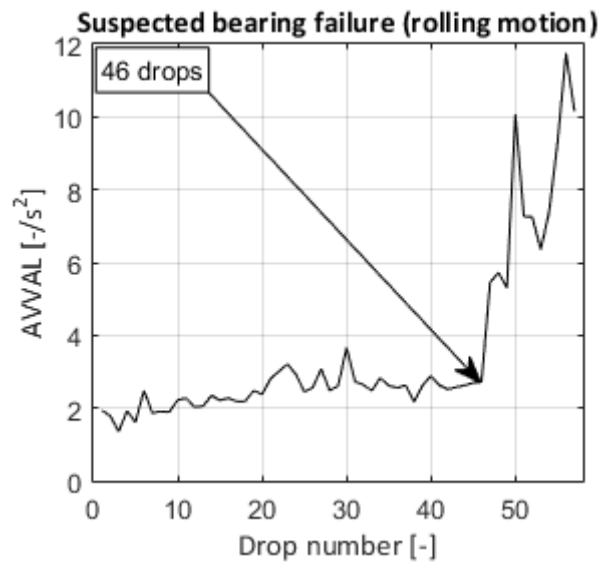


Prediction method settling time

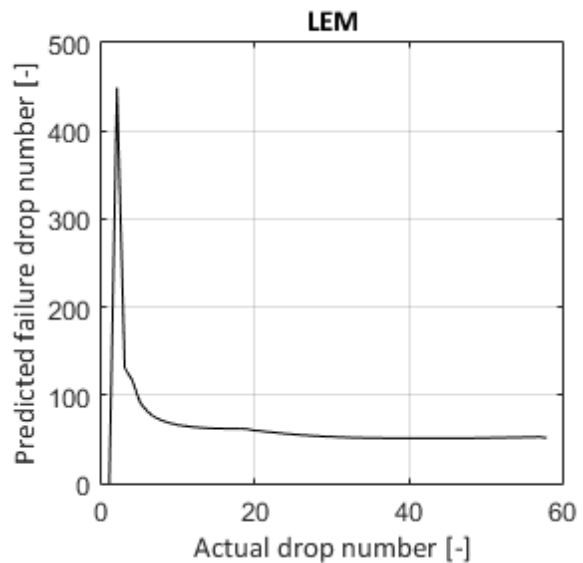
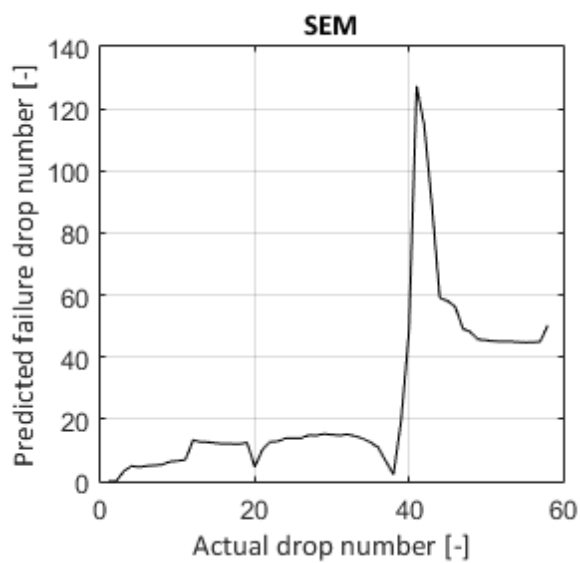


B8. 5000 r/min drop results: Bearing set 3

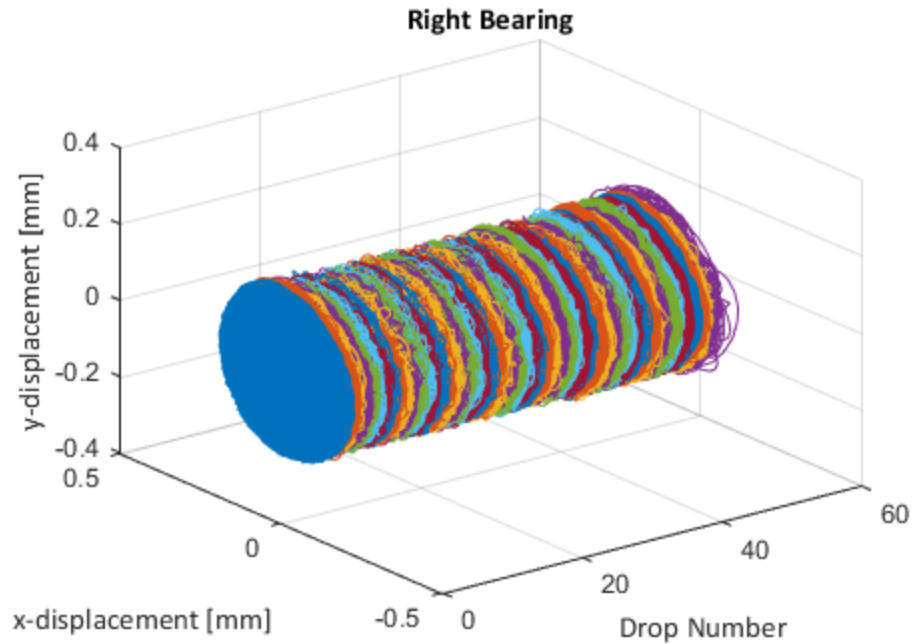
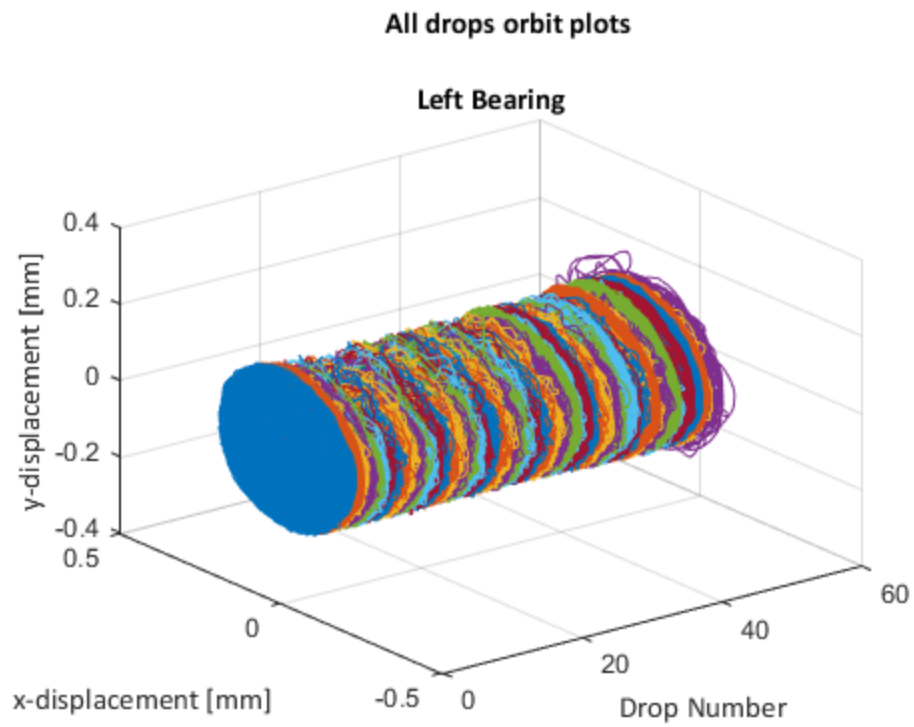


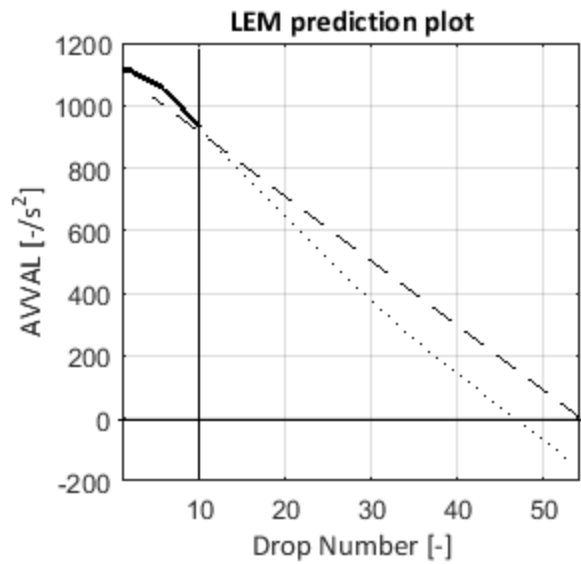
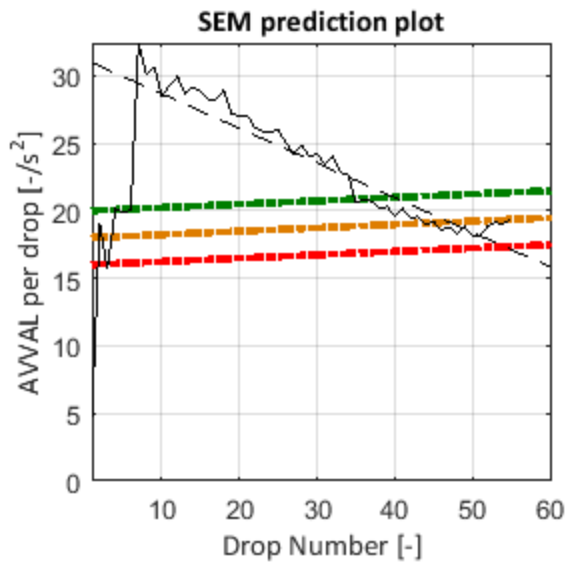
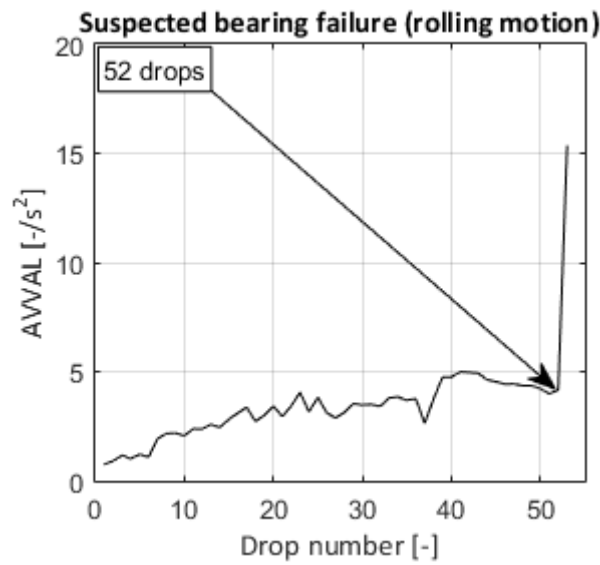


Prediction method settling time

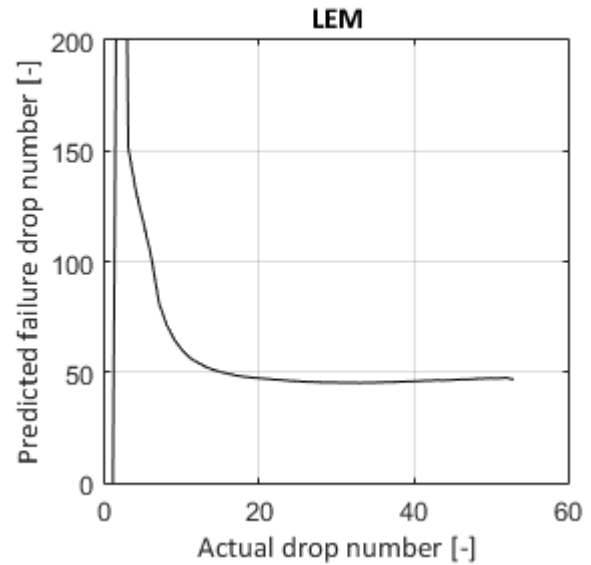
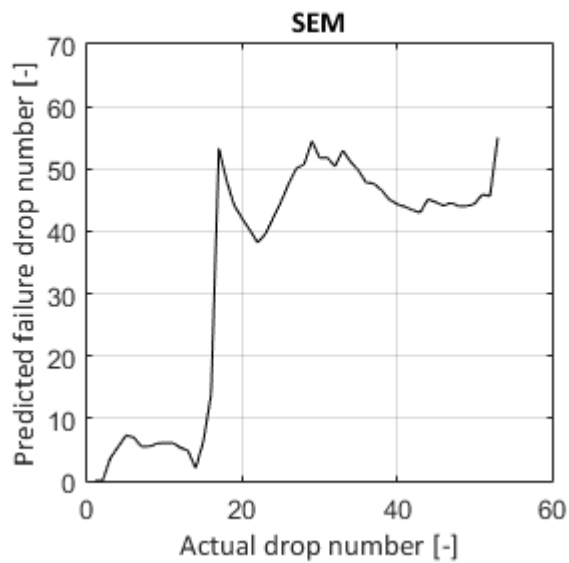


B9. 5000 r/min drop results: Bearing set 4

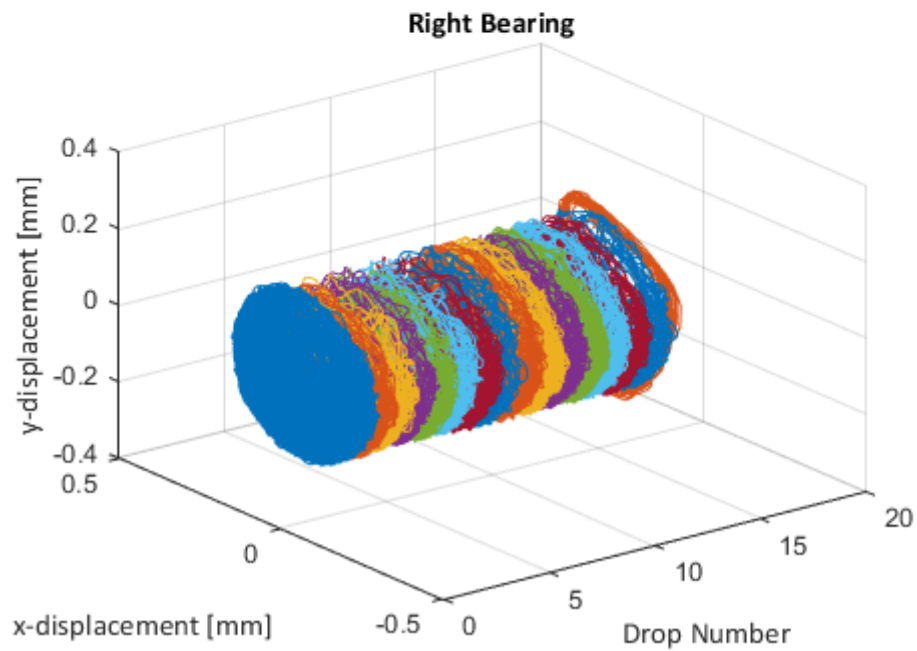
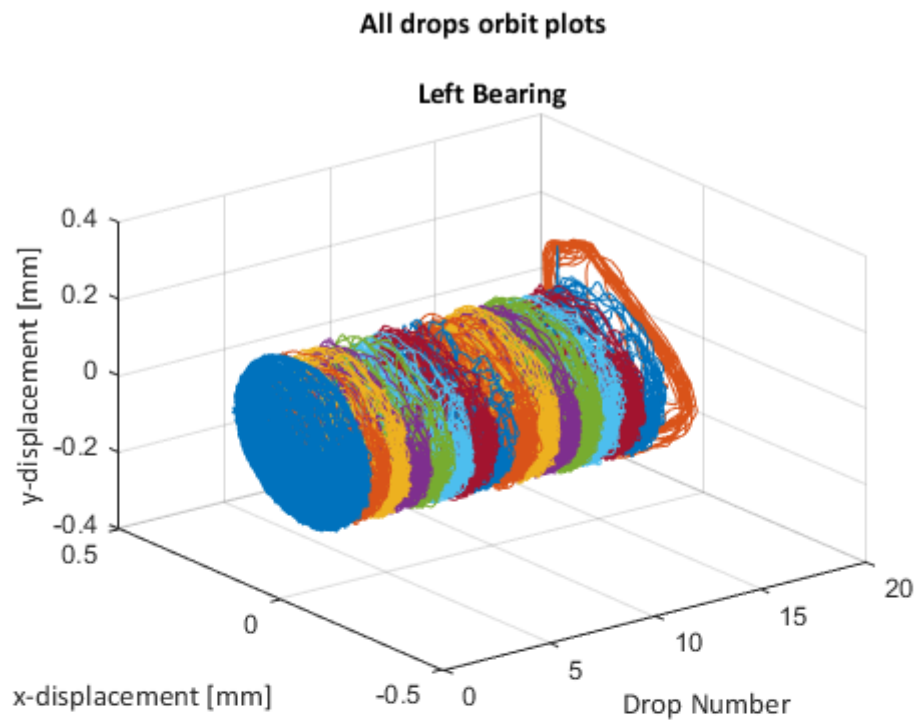


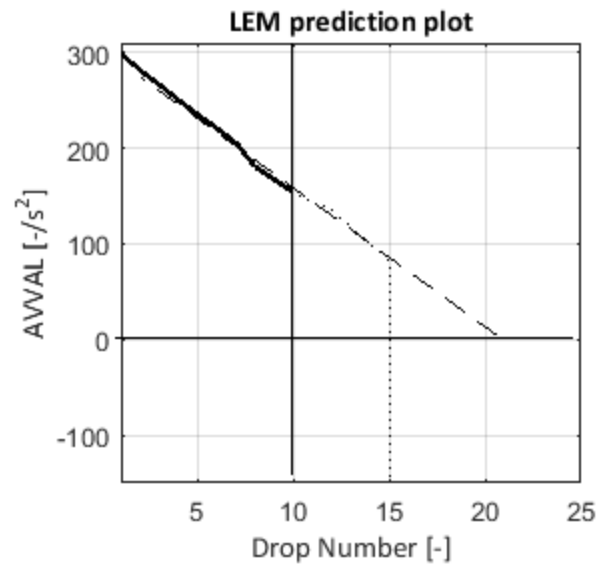
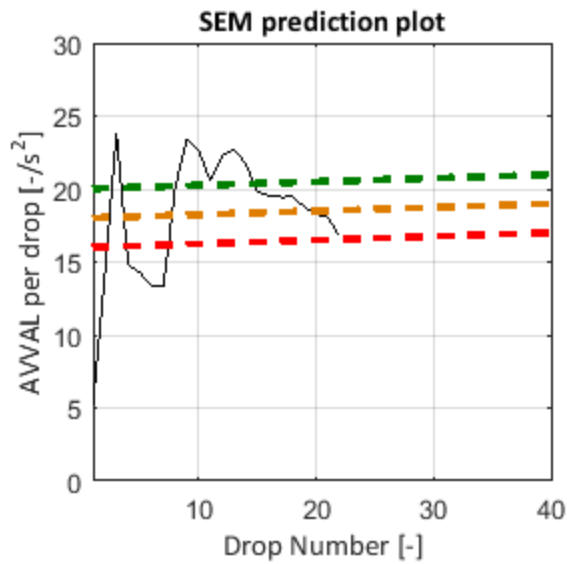
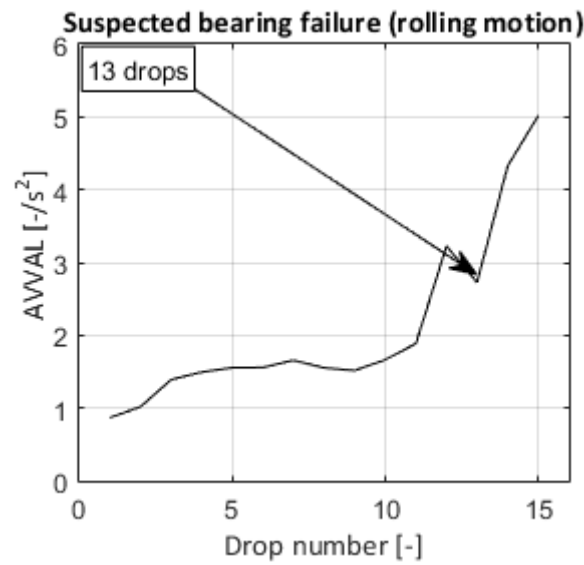


Prediction method settling time

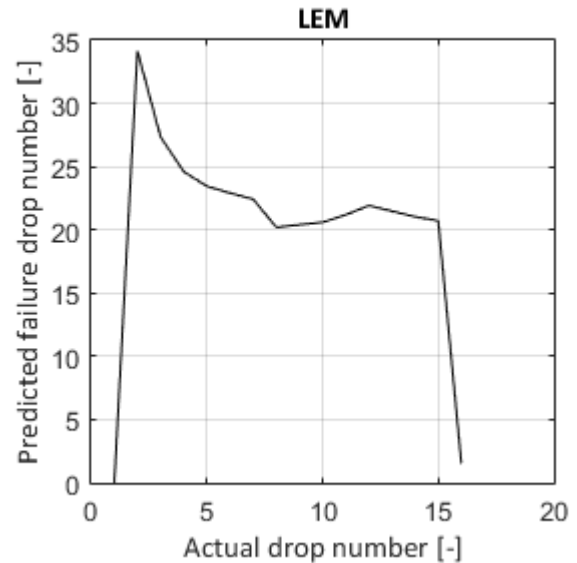
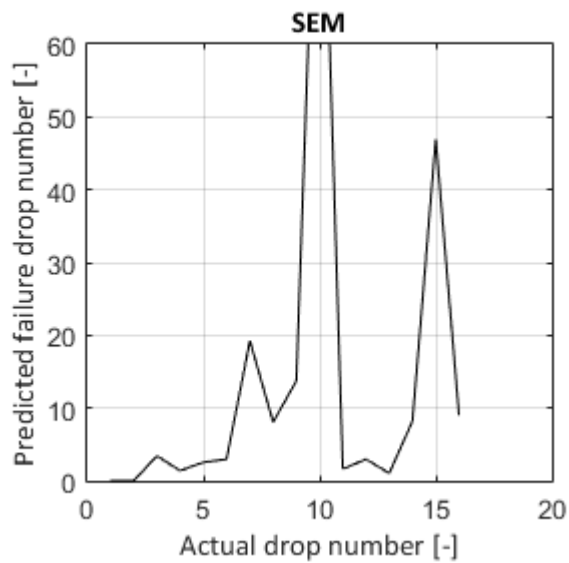


B10. 6000 r/min drop results: Bearing set 1

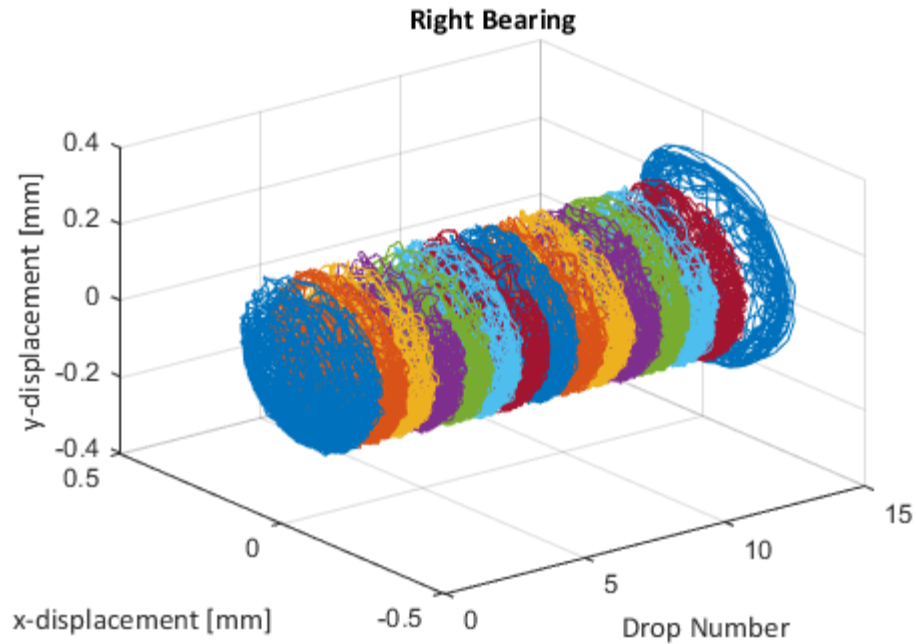
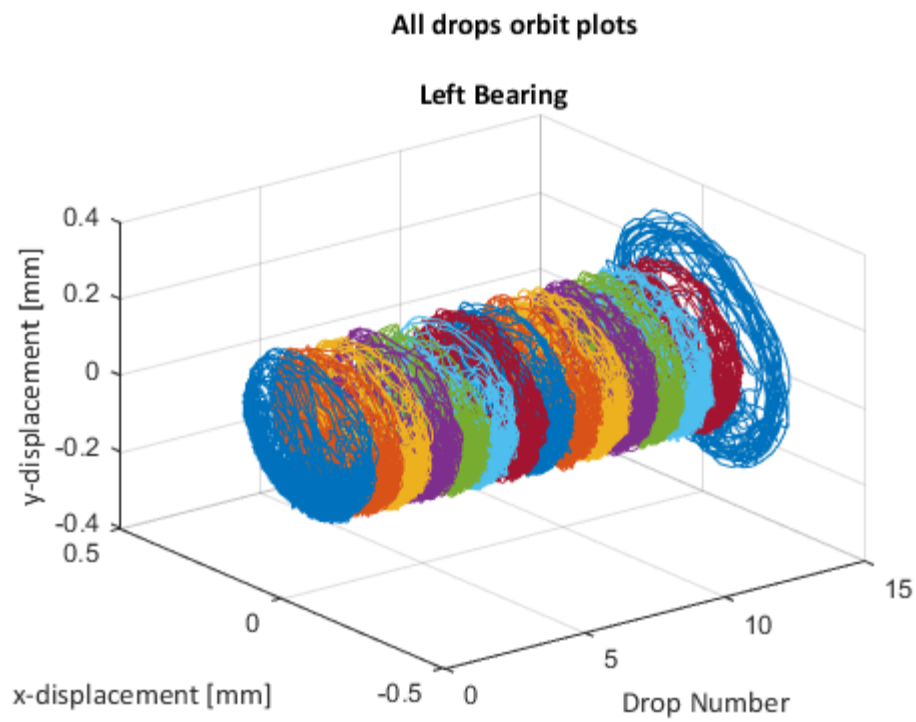


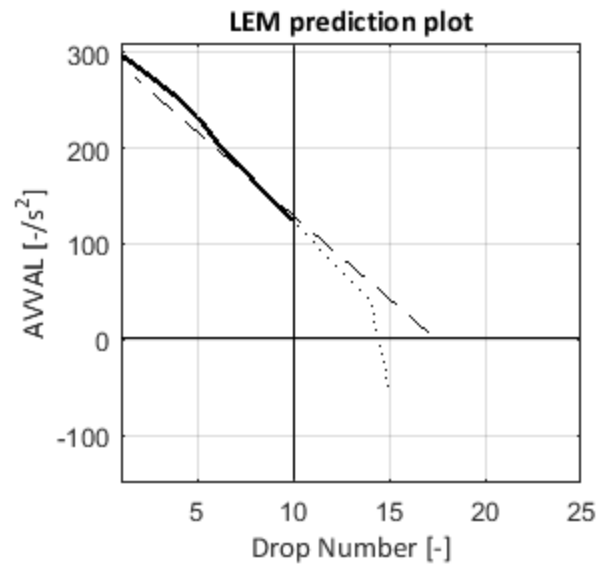
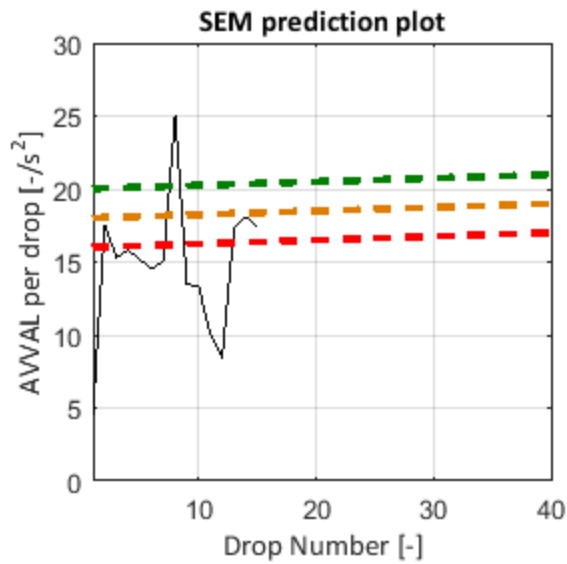
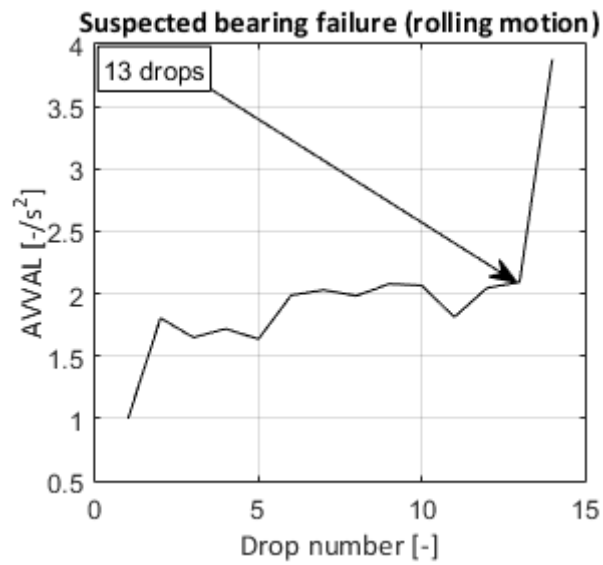


Prediction method settling time

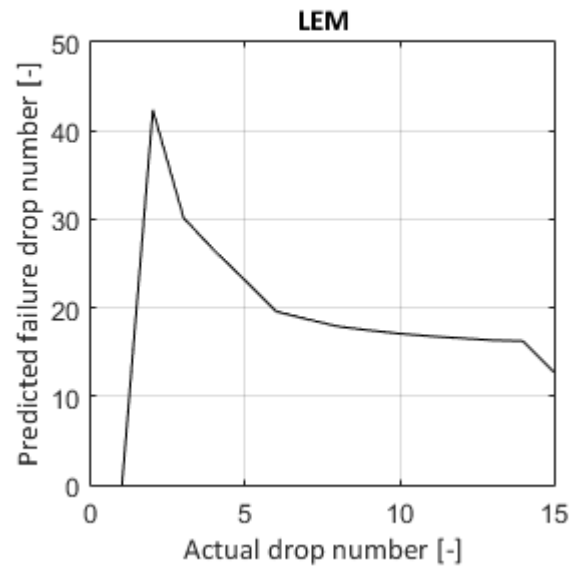
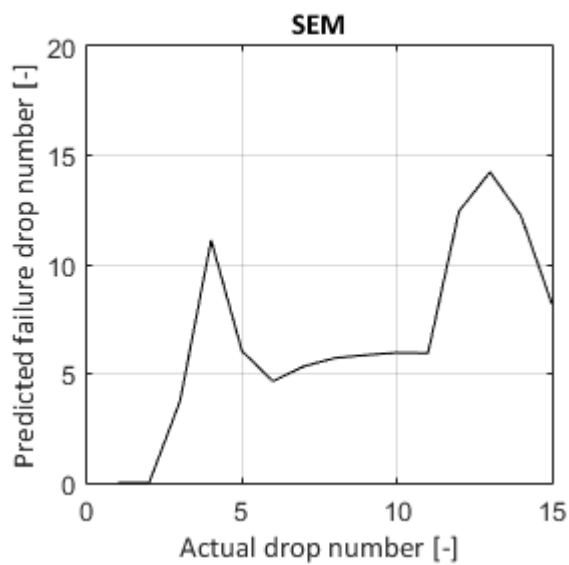


B11. 6000 r/min drop results: Bearing set 2

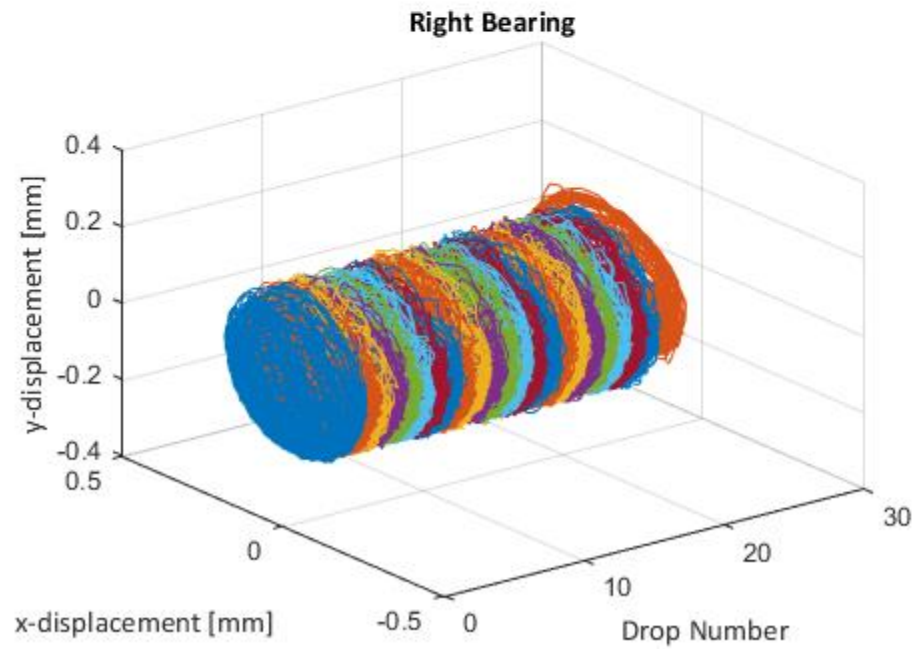
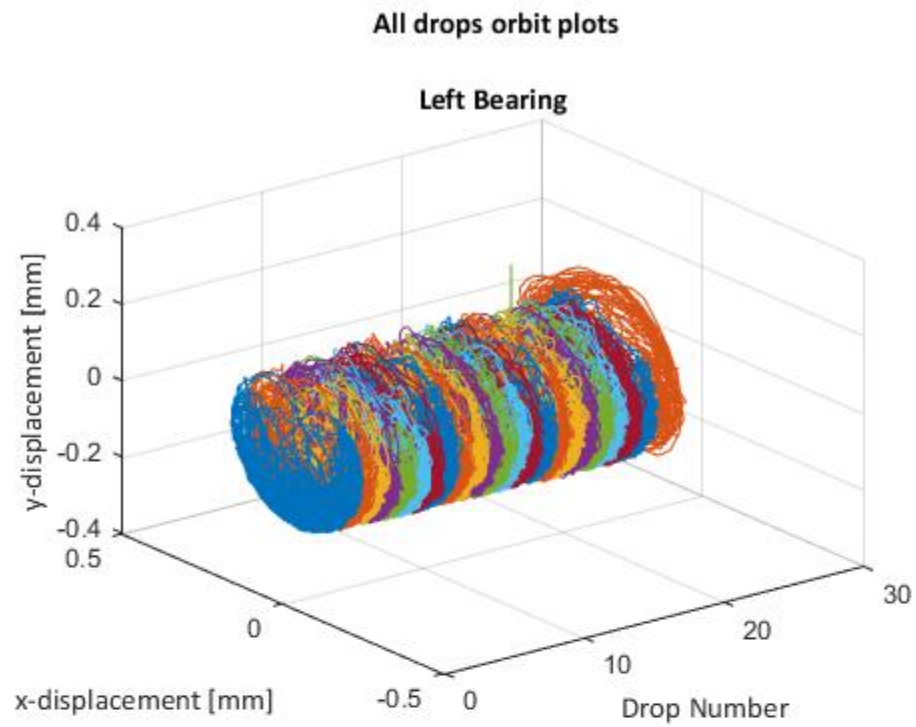


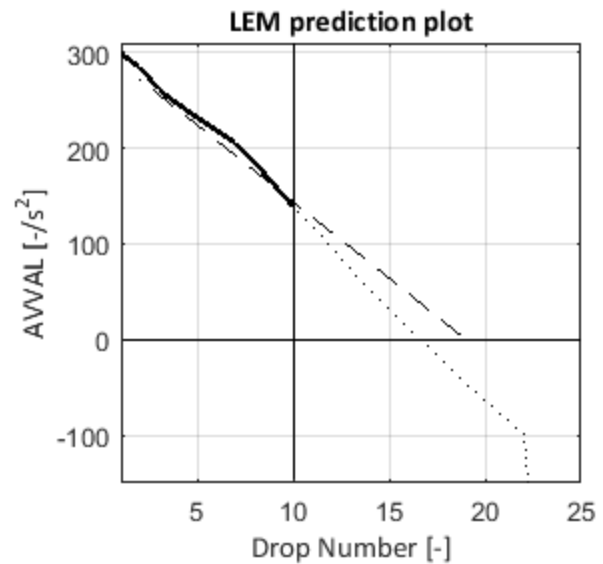
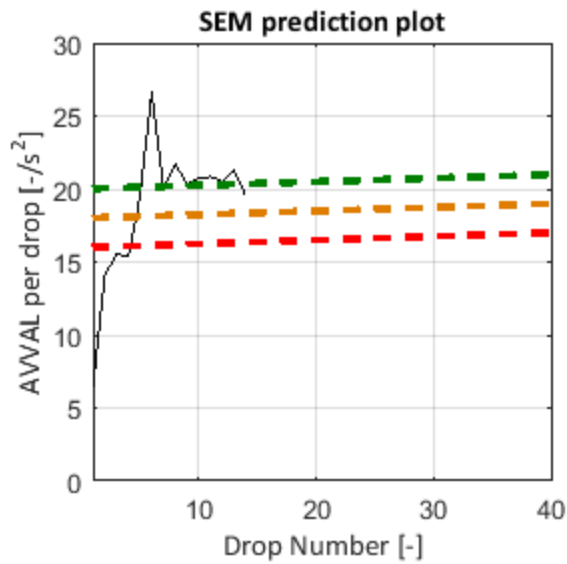
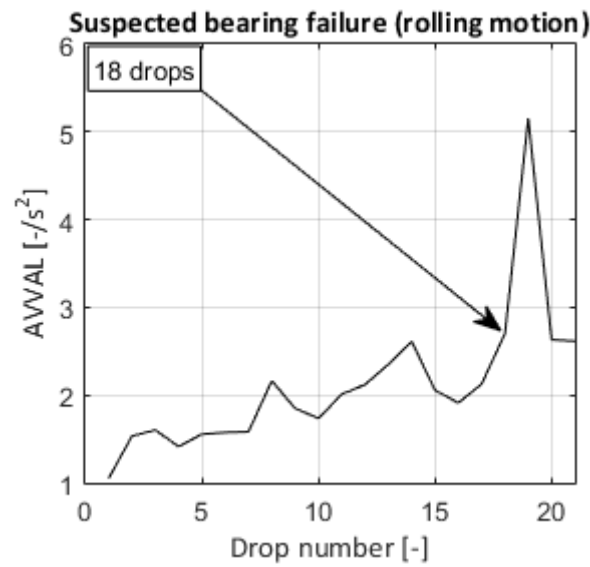


Prediction method settling time

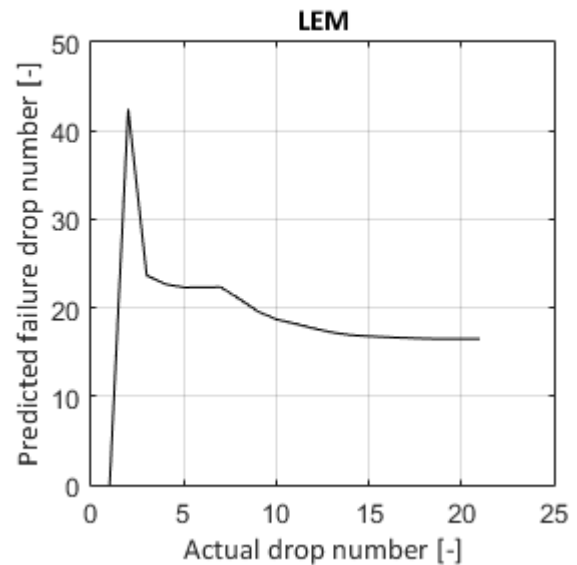
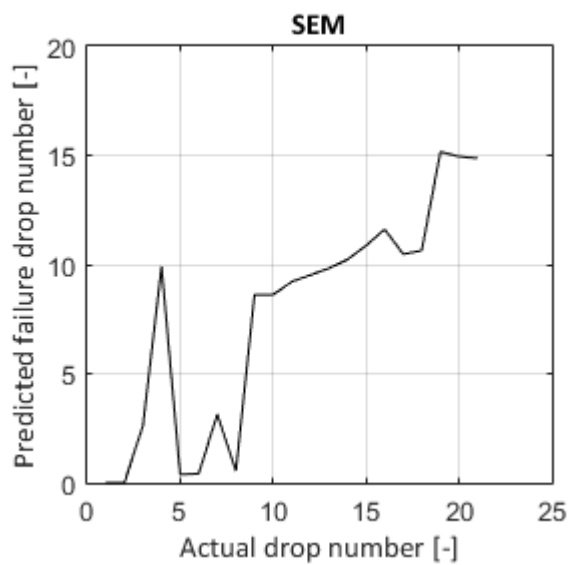


B12. 6000 r/min drop results: Bearing set 3

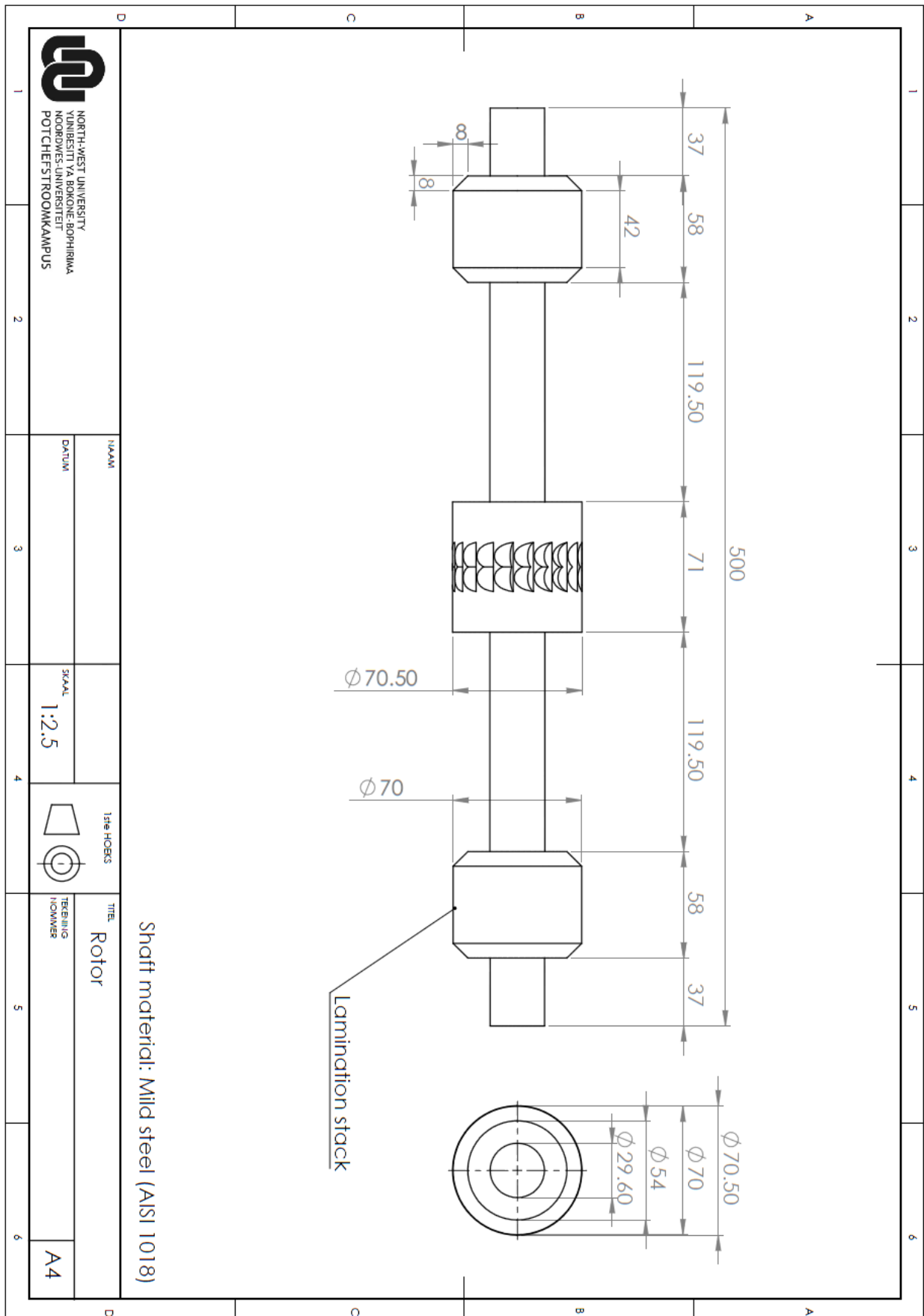




Prediction method settling time



Appendix C. Rotor specifications



Appendix D. Research outputs

This section contains two papers accepted for publication on www.magneticbearings.org . The first paper shown will be presented at the 15th International Symposium on Magnetic Bearings in Kitakyushu-Japan 2016. The second paper was presented at the 10th Workshop on Magnetic Bearings Technology in Zittau Germany, 2015.

The papers follow on page 104-112.

D1. 15th International Symposium on Magnetic Bearings

An Investigation into Backup Bearing Life using Quantified Rotor Delevitation Severity Indicators

Jacob Marthinus GOUWS* and Jan Jacobus JANSE VAN RENSBURG*

* School of Mechanical and Nuclear Engineering, North-West University, Potchefstroom Campus

11 Hoffman Street, Potchefstroom, 2520, South Africa

E-mail: 21662428@nwu.ac.za

Abstract

Safe and continuous operation of an active magnetic bearing (AMB) system relies heavily on its mechanical, electronic and software components. If one of these components fail, a rotor delevitation event (RDE) could be induced and possibly damage the backup bearing (BB) system. To improve BB reliability and safety, the usability of delevitation severity indicators (*DVAL*, *VVAL* and *AVVAL*) for predicting BB life is investigated. A small-scale active magnetic bearing system is used to generate BB degradation data by subjecting steel-caged rolling-element bearings to multiple RDEs. The RDEs are induced at specific initial conditions to analyze the statistical distribution of bearing failure. Delevitation severity indicators are subsequently used to compare a series of RDEs to find changes in BB performance characteristics. Using only shaft position and rotating speed data, this investigation showed that delevitation severity indicators change as the bearing degrades. A distinctive linear pattern of degradation is identified by calculating *AVVAL* for the duration when rotor whirl and bouncing occur. This linear degradation pattern is used to identify a failure zone wherein the probability of bearing failure is extremely high. A BB life prediction method based on this linear degradation pattern and *AVVAL* is developed and validated.

Keywords : Backup Bearing, Auxiliary Bearing, Catcher Bearing, Retainer Bearing, Life Prediction, Active Magnetic Bearing, Quantification, Bearing Degradation

1. Introduction

The use of active magnetic bearings (AMBs) in industrial applications is increasing due to their ability in solving classic rotordynamic problems (Schweitzer & Beuler, 2009). Safe and continuous operation of an active magnetic bearing (AMB) system relies heavily on its mechanical, electronic and software components. If one of these components fail, a rotor delevitation event (RDE) could be induced and possibly damage the backup bearing (BB) system.

The dynamics of RDEs are highly nonlinear and often result in loads exceeding the rated bearing load (Schweitzer, 2005). Numerous mathematical tools and models have been developed to predict rotor behavior during an RDE (Janse Van Rensburg, et al., 2010). These modelling techniques largely neglect the cumulatively degradative effect of individual delevitations on overall BB life. Standard bearing life prediction methods do not directly apply to the nonlinear load conditions to which BBs are mostly subjected. Even though the API 617 (2014) standard provides guidelines towards the minimum allowable full-speed RDEs until bearing failure, very few studies quantifying the effect of multiple RDEs on BB performance and life exist. Testing of an AMB system is almost always required from which the life of the BB system can be established (Swanson, et al., 2014).

Sun (2005) presented a method of estimating the fatigue life of BBs using a Hertzian-contact bearing model. Due to the nonlinear load conditions of BBs, the Lundberg-Palmgren formula used by Sun only applies to cases of steady continuous loading. Lee (2012) evaluates the fatigue life of BBs based on the number of RDEs until failure. The Rainflow counting algorithm is valid for random load conditions commonly found in BB applications. A study conducted by Reitsma (2002) suggested that only shaft-delevitation position and BB clearance monitoring after an RDE possess the potential for BB predictive maintenance capabilities. Janse van Rensburg (2013) submitted a thesis

presenting a method for quantifying the severity of an RDE using only position and velocity data. These delevitation severity indicators can be used to compare subsequent RDEs to find changes in BB performance characteristics. The energy dissipated by the BBs during an RDE is an indication of the degradation of bearing quality caused by delevitation of the rotor (Janse van Rensburg, et al., 2012). Considering the conclusions by Reitsma, the usability of delevitation severity indicators for BB life prediction and degradation quantification is investigated.

A method to predict BB life is derived from large amounts of BB degradation data over a range of initial conditions. BB failure results for numerous bearing sets are shown and used to analyze bearing failure distributions. Delevitation severity indicators are calculated according to different rotordynamic motions and applied to each RDE to identify performance degradation patterns. The degradation patterns are used to develop a life prediction method. In addition, a novel method for quantifying rotor movement is shown (*ADVAL*).

2. Delevitation severity indicators

To measure the severity of an RDE, the overall non-dimensionalized distance travelled by the geometric center of the rotor (*DVAL*) is calculated (Janse van Rensburg, 2013). The distance travelled is non-dimensionalized by dividing it with the airgap radius and represents the number of times the rotor traversed the entire airgap distance. Equation (1) shows the non-dimensionalized distance with i the index number of a time-sampled data point, k the index number up to when the severity of the RDE is calculated, x and y the distance from the geometric center of the BB in the x - and y -direction respectively, and r_{airgap} the clearance between the rotor and the BB inner-race.

$$DVAL(k) = \sum_{i=1}^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap}} \quad (1)$$

The second variable by which the severity of an RDE can be measured is the average non-dimensionalized velocity (*VVAL*), with a unit of s^{-1} (Janse van Rensburg, 2013). Equation (2) shows the non-dimensionalized velocity with $t(k)$ the time when *DVAL*(k) is reached.

$$VVAL(k) = \sum_{i=1}^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap} \cdot t(k)} \quad (2)$$

The final variable for measuring the severity of an RDE is the average non-dimensionalized deceleration (*AVVAL*) with a unit of s^{-2} (Gouws, et al., 2015). Equation 3 shows this non-dimensionalized deceleration.

$$AVVAL(k) = \sum_{i=1}^k \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap} \cdot t(k)^2} \quad (3)$$

By calculating the *DVAL*, *VVAL* and *AVVAL* values for a single RDE, the values for subsequent RDEs can be calculated and compared to find changes in BB performance characteristics.

3. Experimental procedure

The following section contains information on the experimental setup and methods used to gather BB degradation data. Figure 1 shows the small-scale active magnetic bearing system used to induce the necessary delevitation conditions. The rotor has a mass of 7.74 kg and is radially suspended by AMBs and axially suspended by a passive magnetic bearing system. Deep-groove ball bearings (6806) with a bore diameter of 30 mm are used as BBs. For the purposes of this study, all bearing lubrication is removed from the BBs by placing them in a heated ultrasonic acetone bath. Lubricant-free bearings are used to minimize variations associated with thermal effects on lubrication viscosity. The BB system is rigidly mounted with no compliant mounts. A lack of damping support is used to confine degradation to the BBs and minimize the effect of bearing support degradation on overall bearing performance. The rotor-bearing interface has an airgap radius of 200 μm . A simplified sketch of the BB support is shown in Fig. 2.

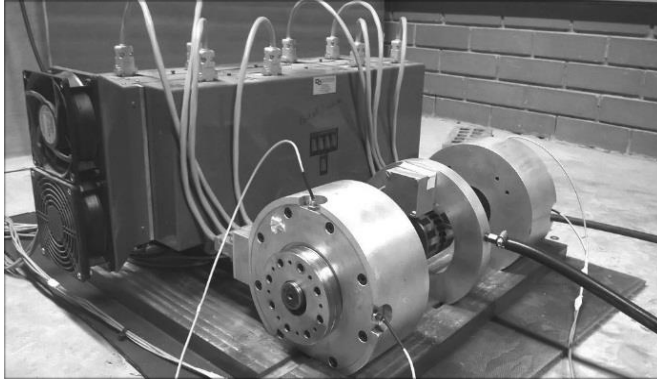


Fig. 1 AMB system used to gather BB degradation data

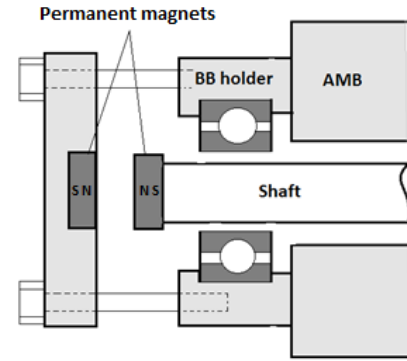


Fig. 2 Simplified sketch of BB system assembly

BB degradation data are obtained by subjecting the BBs to repeated RDEs under various delevitation conditions. The rotor delevitation tests are done by repeatedly levitating and spinning the rotor up to a speed that is 1000 r/min higher than that of the chosen delevitation speed. Once the rotor speed is 1000 r/min higher than that of the delevitation speed, the rotor is allowed to freely spin down and delevitate onto the BBs at a specific speed and angle from the geometric centre of the AMBs. The *DVAL* values for each delevitation are automatically calculated and logged once the RDE occurs. The delevitation process for a specific set of initial conditions is repeated until BB failure is evident. The variables recorded during the rotor drop tests are the *x*- and *y*-position of the rotor within each BB clearance, the *DVAL* value as calculated in real time, the shaft rotating speed, the delevitation duration and the number of drops until bearing failure

4. Experimental results

This section contains information on the experimental results obtained using the methods described in the previous section. Bearing failure analysis and degradation quantification are shown. The usability of delevitation severity indicators for BB life prediction purposes is also investigated.

4.1 Bearing failure analysis

BB degradation data were gathered by subjecting ten separate sets of BBs to multiple RDEs at four different initial conditions. By inducing multiple RDEs at different initial conditions, the repeatability and characteristic nature of BB failure were investigated. Figure 3 shows the number of RDEs until failure at each initial condition. Failure detection was achieved by RDE position trending, orbit plot trending, hand roll checks and shaft rotational speed trending. Figure 4 shows an example of the orbit plot trending used to study changes in rotor-bearing touchdown dynamics for a BB set exposed to numerous 4500 r/min RDEs until failure. All of the discussed failure detection methods were able to detect when BB failure occurred. The methods, however, proved to be unusable since BB failure was only noticed once catastrophic failure of the bearing cage occurred. BB failure was always characterized by seizure of the rolling elements and severe backward whirl. No change in bearing condition and/or change in bearing performance characteristics between RDEs could be detected with the failure detection methods discussed. BB failure only occurred at one bearing location at a time and alternated randomly between bearing locations. The random nature of the failure location is indicative of differences in bearing manufacturing quality and BB alignment. Inconsistent bearing failure patterns and unsatisfactory condition monitoring capabilities could cause BB delevitation even after possible low-severity failure occurred. The need for a life prediction and degradation quantification method is justified when considering the violent rotordynamic motions at failure.

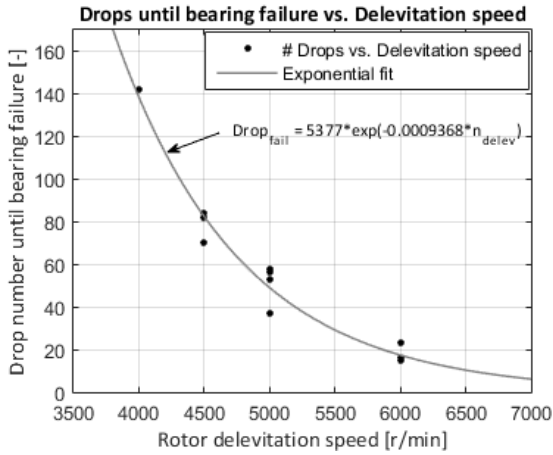


Fig. 3 Number of RDEs until failure

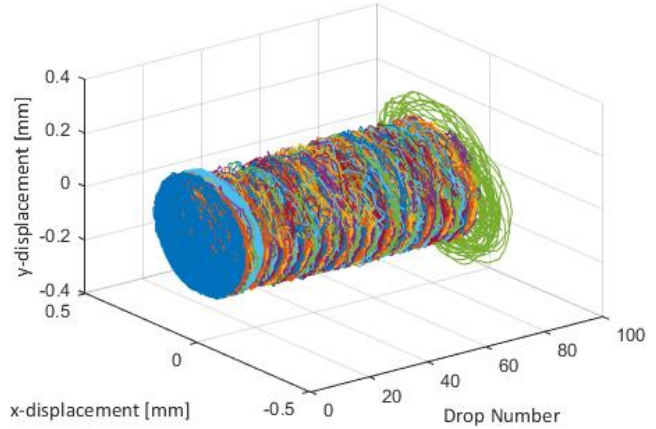


Fig. 4 Orbit plots for multiple 4500 r/min RDEs

4.2 Bearing degradation quantification and analysis

This section contains information on the method used to quantify bearing degradation. Changes in rotor delevitation quality are studied by using delevitation severity indicators to quantify and compare degradation for various bearings subjected to multiple RDEs until failure. A rotor can be subjected to various rotordynamic states during an RDE that can be either one or a combination of the following: rolling, oscillation, bouncing, forward whirl, or backward whirl. The above-mentioned rotordynamic states differ in their destructive nature towards the BBs. For the purposes of this study, it is assumed that some rotordynamic motions have minimal to negligible effects on overall bearing life. Delevitation severity indicators will be calculated according to the most severe rotordynamic motions for degradation quantification and life prediction purposes. The following section contains information on the method used to identify the frequencies at which the most severe rotordynamic motions occur.

4.2.1 Rotordynamic analysis

The rotordynamic analysis used to identify when the most severe rotordynamic motions occur is based on shaft position and rotor speed data. The indicator *DVAL* is calculated and differentiated with respect to time for a single delevitation to yield the number of times per second that the airgap distance is travelled. This $\Delta DVAL$, when plotted against rotor speed, yields the severity of various rotordynamic motions within various stages of an RDE. Figure 5 shows a rotordynamic analysis using $\Delta DVAL$. The three delevitations in Fig. 5 were initiated at different rotor speeds from which three main rotordynamic states are identified. The rotordynamic states are labeled Case A, B and C. The actual rotor orbit during these rotordynamic states are also shown using orbit plots.

Closer inspection of Fig. 5 shows that the type and magnitude of rotor movement are independent of the delevitation speed. The most severe transverse movement is between 6000 and 2500 r/min. For all delevitations up to point 1, a combination of heavy bouncing and forward whirling occurs. Between point 1 and 2, a clear increase and then a sudden decrease in rotor movement occur as the system critical frequency is traversed. The large peaks present within the 4500 and 4000 r/min delevitations show the moment when full forward whirl occurred. The 6000 r/min delevitation failed to enter a state of full forward whirl, hence the absence of a large peak. Between point 2 and 3, a combination of light forward whirl and mostly oscillation occurs. Point 3 up to point 4 shows the moment when the rotor enters the first critical frequency and a state of almost pure oscillation. Even though the peak after point 3 seems similar to the one found between point 2 and 3, their respective motions differ considerably. The first peak contains a combination of light forward whirl and oscillation whilst the second peak exhibits no forward whirl. From point 4 up to where rotor standstill is reached, persistent contact with the BBs is mostly maintained as a rolling motion is induced.

Having assumed that rotor oscillation and rolling have a negligible effect on overall BB life, delevitation severity indicators are calculated over the timespan where the most severe rotordynamic motions occur. From Fig. 5 it is identified that the most severe rotordynamic motion occurs between the point of delevitation and 2500 r/min.

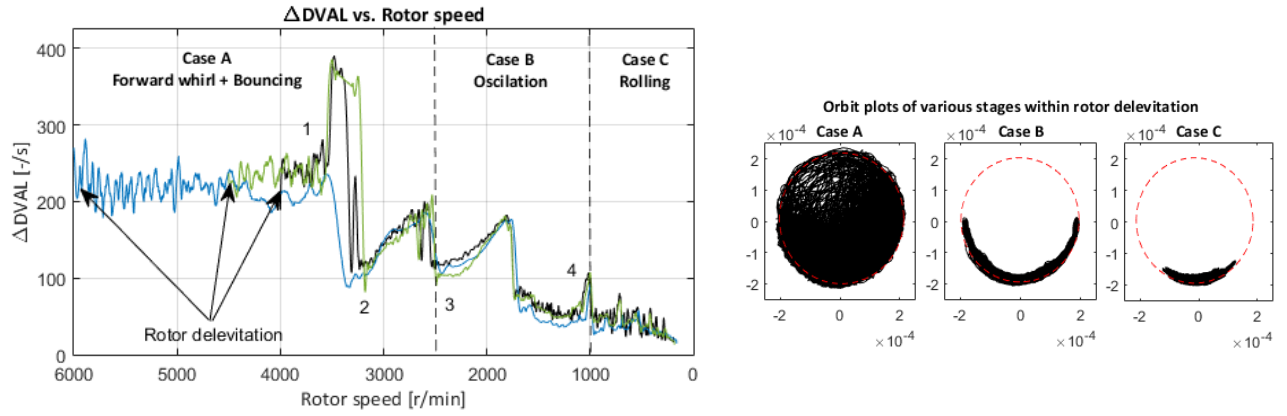


Fig. 5 Rotordynamic response analysis using $\Delta DVAL$

4.2.1 Degradation quantification

Degradation is quantified by calculating and comparing delevitation severity indicators for each RDE of a bearing subjected to multiple RDEs until failure. Figure 6 shows the calculated $DVAL$, $VVAL$ and $AVVAL$ values of a bearing subjected to multiple 4000 r/min delevitations until failure. The delevitation severity indicator values were calculated over the period when rotordynamic motion was most severe (4000-2500 r/min). Similar results were found at both bearing locations due to complete AMB system symmetry. Consequently, only one bearing location is used for calculations.

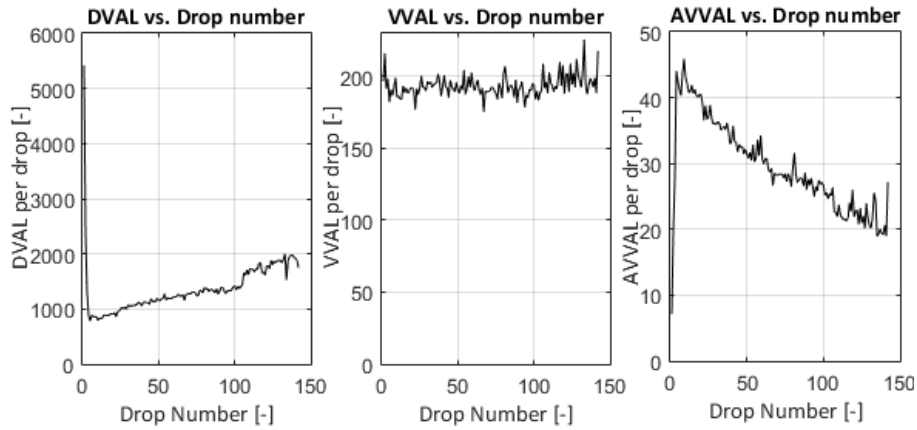


Fig. 6 142 delevitations at 4000 r/min quantified using $DVAL$, $VVAL$ and $AVVAL$

From Fig. 6 it is clear that the maximum $DVAL$ value increases as the drop number increases whereas the $AVVAL$ value decreases as the drop number increases. The $VVAL$ value does not yield any clear indication of changes in BB performance but does indicate that the change in rotor movement is equal to the change in time between delevitations. The equal change in time and transverse movement explains the decreasing $AVVAL$ value, where any change in time will have a non-linear influence on the magnitude of $AVVAL$. The very high $DVAL$ and very low $AVVAL$ values within the first few RDEs are caused by bearing run-in. The noise present between drops is mainly caused by inconsistencies in the initial conditions and some position sensor noise.

Experimental work during this study has shown that the delevitation severity indicators do not seem to change if the BB condition remains the same. The change in delevitation severity indicators between RDEs suggest that changes in BB performance characteristics have occurred.

The indicator $AVVAL$ proved to be the most sensitive to changes in BB performance during experimental work and will be discussed in the remainder of this section.

Calculating $AVVAL$ for bearings subjected to multiple RDEs at different initial conditions, a distinctive linear degradation pattern similar to that of Fig. 6 is obtained. Fig. 7 (left) shows the calculated $AVVAL$ values for various sets of BBs subjected to multiple delevitations until failure occurred. Upon closer inspection of Fig. 7 (left), a threshold indicative of a failure zone wherein bearing failure is extremely likely can be identified. Fig. 7 (right) shows the failure

zone. The failure zone line is based on the statistical distribution of failure for all of the BB sets.

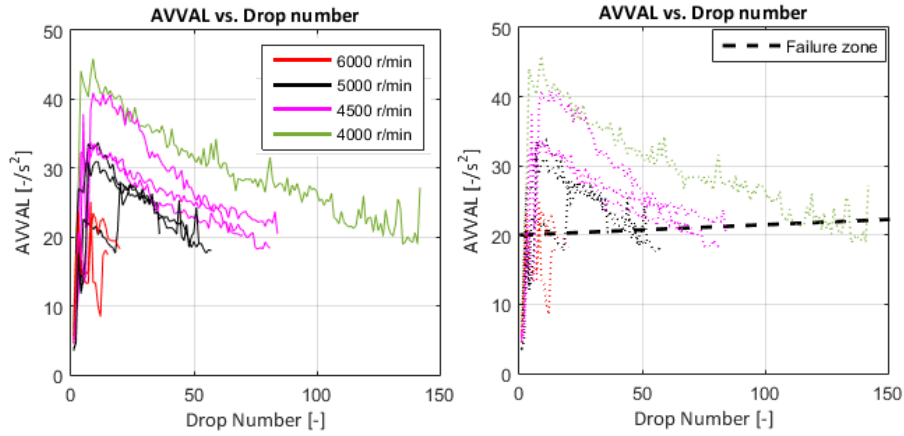


Fig. 7 Failure zone obtained from quantifying degradation for multiple delevitation conditions

The BB life prediction method is based on a combination of statistical bearing failure distributions, identified linear degradation patterns, and the failure zone in Fig. 7. Bearing life is determined by implementing a linear fit to the first few drops after bearing run-in. A straight-line equation from the bearing's *AVVAL* history is used to determine the intersection with the failure zone line. Figure 8 shows an example of the method used to predict bearing life based on the rotor delevitation history.

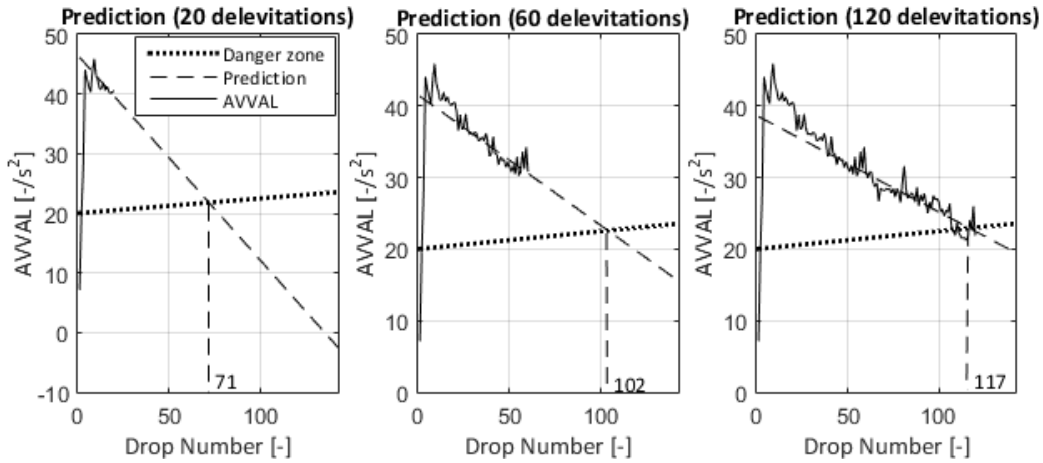


Fig. 8 Delevitation severity indicator in BB life prediction example

5. Validation of life prediction method

Validation was performed by inducing multiple RDEs at various delevitation conditions and comparing the predicted number of drops to failure with the actual number of drops to failure. Bearings from two different manufacturers were repeatedly subjected to various delevitation conditions until catastrophic bearing failure occurred. The two different bearing manufacturers are respectively named manufacturer A and manufacturer B and the bearing cages differed in quality.

To calculate delevitation severity indicators according to the most severe rotor movement required a rotordynamic analysis of both manufacturer bearings. Using *ADVAL*, the frequencies for manufacturer A and manufacturer B were respectively found to be at 2310 r/min and 2500 r/min. The difference in bearing cage quality resulted in varying rotor-bearing touchdown dynamics. The *AVVAL* values for each RDE were calculated and compared according to the above-mentioned critical frequencies. Figure 9 shows an example of the linear fits used to predict BB life for seven individual sets of BBs according to their respective calculated *AVVAL* values.

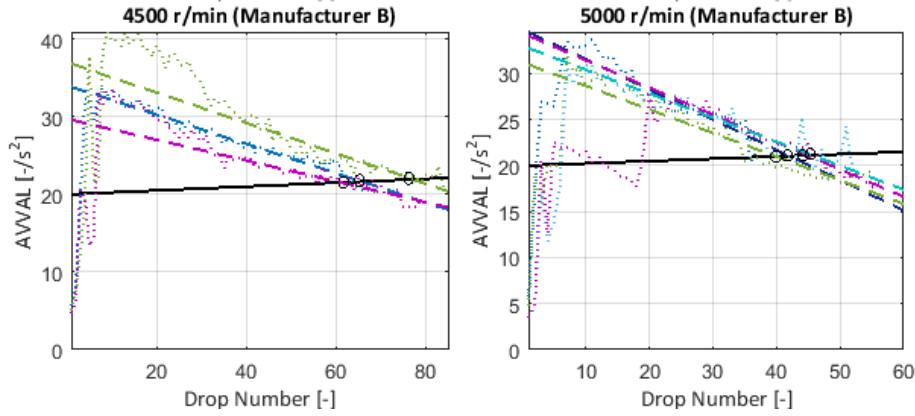


Fig. 9 Delevitation severity indicator life prediction validation

Table 1 shows a summary of various bearing sets subjected to multiple RDEs until failure occurred. A summary of the predicted failure values is also shown. The decreased bearing cage quality from the manufacturer A bearings produced inconsistent bearing failure results. Bearing failure at high-speed delevitations occurred between 1 to 10 drops for this manufacturer. Due to this, testing for this specific manufacturer was limited to 3000 r/min only.

Table 5 Summary of the validation results

	Manufacturer A 3000 [r/min]		Manufacturer B 4000 [r/min]		Manufacturer B 4500 [r/min]		Manufacturer B 5000 [r/min]	
Bearing set	Predicted drop#	Failure drop#	Predicted drop#	Failure drop#	Predicted drop#	Failure drop#	Predicted drop#	Failure drop#
1	57	60	118	118	70	82	40	46
2	39	43	109	104	65	70	41	37
3	-	-	-	-	77	77	44	46
4	-	-	-	-	-	-	46	52

From Table 1 an average prediction accuracy of 91 % over all delevitation conditions were found. It is also interesting to note that 82% of the predicted failure drop numbers were lower than the actual failure drop numbers.

6. Conclusions

The following conclusions can be made from the research presented. BB failure was always characterized by seizure of the rolling elements and severe backward whirl. No change in bearing condition and/or change in bearing performance characteristics between RDEs could be detected with basic failure detection methods. AMB vendors are advised to implement some form of preventative maintenance or condition monitoring on the BB system to improve reliability and safety. Quantifying and comparing the severity of various RDEs showed that delevitation severity indicators change as the bearing degrades. The ability to quantify this change over a series of RDEs provides some potential for condition monitoring capabilities. Calculating *DVAL* and *AVVAL* according to the most severe rotordynamic motions showed that distinctive linear degradation patterns exist. The linear degradation pattern was only clear once full bearing run-in occurred. A threshold for *AVVAL* in the form of a failure zone was also identified. The energy dissipated by the BBs during an RDE is an indication of the degradation of bearing quality caused by delevitation of the rotor (Janse van Rensburg, et al., 2012) . Rotor whirl, bouncing, oscillation and rolling all differ in their degradative nature towards the BBs. The *AVVAL* threshold suggests a maximum cumulative amount of energy that the rolling elements can absorb before failure occurs. More study into this phenomenon will, however, be required. Quantifying degradation when rotor oscillation and rolling occur is not shown in this paper because it did not produce linear degradation patterns and/or failure thresholds. Quantifying degradation during a rolling motion did provide some early-failure detection capabilities.

Using delevitation severity indicators to quantify bearing degradation enabled some rudimentary life prediction capabilities. The life prediction method was found to be applicable only when BB life exceeded that of the bearing's

run-in phase. A minimum of 12 RDEs was required to determine linear trends within the degradation data. Bearing life was found to be drastically influenced by bearing manufacturing quality. Bearings of similar rating but different manufacturers subjected to the same conditions varied in overall bearing life. The large dependence of bearing quality on overall bearing life could complicate modelling and simulation-based life prediction methods.

A novel method for quantifying rotor movement was developed using *ADVAL*. This method enables critical frequency analysis of the BB system, identification of rotor delevitation severity, and forward- or backward-whirl detection capabilities. Different rotordynamic motions were found to depend on the rotor traversing specific critical frequencies of the AMB system. The magnitude of transverse movement was also found to be independent of the delevitation speed. Application of this method would consist of the comparison of rotor delevitation quality by various BB manufacturers for design and implementation purposes. This method also has potential as a verification tool for simulation-based methods.

Recommended future work includes the integration of delevitation severity indicators in RDE modelling. The effect of BB support stiffness and damping on life prediction methods should further be studied. An investigation of the effect of cage-less ceramic or lubricated bearings on life prediction methods is also recommended. A method for determining the identified failure thresholds from basic system variable is also required.

7. Acknowledgements

Our appreciation to the McTronX research laboratory and Prof. George van Schoor for the use of equipment and his guidance. Secondly, we would like to thank Eskom, the national power utility company of South-Africa, for financial support.

References

- Janse van Rensburg, J. J., van Schoor, G. & van Vuuren, P. A., The characterization of the severity of rotor delevitation events: A parametric study, Proceedings of the 13th International Symposium on Magnetic Bearings (2012).
- Gouws, J. M., Janse van Rensburg, J. J. & Vanek, C., Backup-Bearing lifetime prediction using quantified delevitation severity indicators, Proceedings of the 10th Workshop on Magnetic Bearings (2015).
- Janse van Rensburg, J. J., Delevitation modelling of an active magnetic bearing supported rotor, PhD Thesis (2013),
- Janse van Rensburg, J. J., van Schoor, G. & van Vuuren, P. A., Delevitation Modelling of an Active Magnetic Bearing Supported Rotor, Proceedings of the 12th International Symposium on Magnetic Bearings (2010)
- Lee, J. G, A Nonlinear Transient Approach for Morton Synchronous Rotordynamic Instability and Catcher Bearing Life Prediction, PhD Thesis (2012)
- Reitsma, T. W., Development of Long-Life Auxiliary Bearings for Critical Service Turbomachinery and High-Speed Motors. Proceedings of the 8th International Symposium on Magnetic Bearing (2002)
- Schweitzer, G., Safety and Reliability Aspects for Active Magnetic Bearing Applications - A Survey, Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, (2005), pp. 383-392.
- Schweitzer, G. & Beuler, H., Magnetic bearings: theory, design, and application to rotating machinery. (2009), Verlag Berlin Heidelberg: Springer Science & Business.
- Standard, API 617, Axial and Centrifugal Compressors and Expander-Compressors for Petroleum, Chemical and Gas Industry Services, American Petroleum Institute (2014), Eighth Edition
- Sun, G., Auxiliary Bearing Life Prediction Using Hertzian Contact Bearing Model. Journal of Vibration and Acoustics, 9 September (2005), pp. 203 - 209.
- Swanson, E., Masala, A. & Hawkins, L, New Active Magnetic Bearing Requirements for Compressors in API 617 eighth edition (2014)

BACKUP-BEARING LIFETIME PREDICTION USING QUANTIFIED DELEVITATION SEVERITY INDICATORS

JM. Gouws, JJ. Janse van Rensburg

*School for Mechanical and Nuclear Engineering
North-West University of Potchefstroom
Hoffmanstraat 11*

2520 Potchefstroom, South-Africa

Tel.: +2718299-1111, Fax: +2718299-2767

Email: 21662428@nwu.ac.za, jan.jansevanrensborg@nwu.ac.za

C.Vanek

*Department of Mechatronic Systems
University of Applied Sciences Zittau
Theodor-Körner-Allee 16*

02763 Zittau, Germany

Tel.: +493583612239, Fax: +493583611288

Email: c.vanek@hszg.de

Abstract

In order to improve backup bearing reliability and safety, the applicability of using quantified delevitation severity indicators *Dval*, *Vval* (as described in [1]) and *AVval* for predicting backup bearing life is investigated. Degradation data is gathered using a small-scale experimental test bench to delevitate a rotor under specific initial conditions and simultaneously logging the *Dval* value for several repeated rotor delevitation events (RDEs). Three individual sets of backup bearing degradation data is shown indicating that delevitation severity indicators change as the bearing degrades. This change could enable condition monitoring of the backup bearings where the ultimate goal of this research is to induce repeatable backup bearing failures, and subsequently analyse the *Dval*, *Vval* and *AVval* data in order to predict future failures on a new set of backup bearings.

1 Introduction

Active magnetic bearings (AMBs), being a mechatronic system, are inherently flawed in terms of possible failure from either mechanical, electronic or software components. Failure of any of these components could induce an RDE during operation and, possibly degrade the backup bearing system. Quantifying backup bearing (BB) degradation and ultimately predicting

backup bearing life is a difficult task due to the high dependence on the initial conditions and the non-linear nature of delevitation events [2]. This can be seen in the fact that there are rather few literature sources currently available on backup bearing lifetime prediction. The existing methods used for predicting backup bearing life are unsatisfactory due to limited real time implementation and unsatisfactory condition monitoring capabilities on most commissioned AMB systems.

2 Backup-bearing life time prediction in literature

In 2005, Sun [3] presented a method of predicting the estimate fatigue life of BBs using a Hertzian-contact bearing model. The bearing fatigue life is calculated through the dynamic loads that occur between the bearing ball and races during an RDE. By using a one-dimensional thermal model, the thermal growth can be predicted in various components. In Sun's [3] research, a Lundberg-Palmgren formula was utilized. This formula is only valid for steady continuous loading, which does not always reflect real world BB conditions [4]. In [4] Lee utilized the rainflow counting algorithm to evaluate the fatigue life of BBs in terms of the number of

delevitation events that could occur before BB failure. This involved calculating the contact load, sub-shear stress, Hertzian stresses, thermal growths and surface shear stress. This [4] investigation found that reduced contact friction, decreased bearing air gap, decreased operating speed, decreased support stiffness and increased damping all contributes to increased service life of the BB system. Another conclusion was that large imbalance increases the possibility of forward whirl occurring. In [5] a development program was undertaken by Reitsma to develop a long life BB system capable of withstanding multiple delevitations for critical service turbo machinery and high speed motors. This program included the development of modelling and simulation tools, identification, testing and optimization of full scale test setups. Amongst various other results, it was found that all the failure detection methods used during the investigation was able to identify when a BB failure had occurred. It was also concluded that the only method showing true potential for predictive maintenance capabilities was through the use of shaft delevitation position data and BB clearance monitoring after an RDE.

3 Delevitation severity indicators

In order to measure the severity of a rotor drop, the overall non-dimensionalised distance travelled by the geometric centre of the rotor ($Dval$) is calculated [6]. The distance travelled is non-dimensionalised by dividing it with the air-gap radius, which represents the number of times the rotor travelled the entire air-gap distance. Equation (1) shows the non-dimensionalised distance with i the index number, k defined as the index number where the rotational speed is equal to a predefined value lower than the first critical speed of the system, x and y the distance from the geometric centre of the backup bearing in the x and y -direction respectively, and r_{airgap} the clearance between the rotor and the backup bearing inner race.

$$Dval(i) = \frac{\sum_{i=1}^k \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{r_{airgap}} \quad (1)$$

Another method, in which the severity of an RDE can be measured, is the average non-dimensionalised velocity ($Vval$) with a unit of per second. Equation 2 shows the non-dimensionalised velocity with $t(k)$ the time at which $Dval(k)$ is reached.

$$Vval(i) = \frac{Dval(i)}{t(k)} \quad (2)$$

The final method presented for measuring the severity of an RDE is the average non-dimensionalised deceleration ($AVval$) with a unit of per second squared. Equation 3 shows the non-dimensionalised deceleration.

$$AVval(i) = \frac{Dval(i)}{t^2(k)} \quad (3)$$

By calculating the $Dval$, $Vval$ and $AVval$ value for a single rotor drop, the values for subsequent rotor drops can be calculated and compared in order to find any changes within backup bearing performance characteristics. The following figures are shown in order to illustrate how $Dval$ can be used to quantify a single rotor drop where Fig. 1 shows the orbit plot of a delevitation done at 4500 r/min.

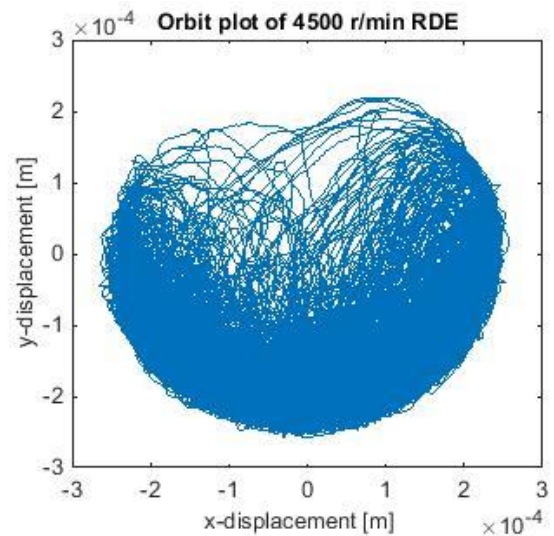


Fig.1: Orbit plot of 4500 r/min Delevitation

Fig. 2 shows the calculated $Dval$ value plotted against revolutions per minute of the orbit plot illustrated above.

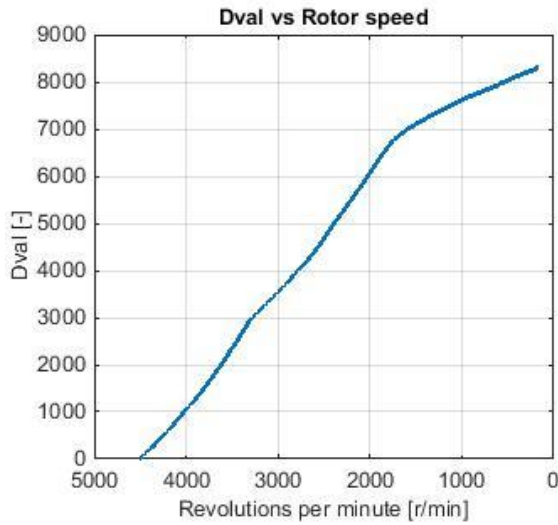


Fig.2: 4500 r/min Delevitation Quantified using $Dval$

A steeper slope of the $Dval$ plot indicates a larger amount of transverse movement taking place. Upon further inspection of Fig. 2, small bumps within the plot can be found. This is where rotor traverses critical frequencies and increased tendency towards forward whirl occurs, especially at the second major critical frequency found at 3228r/min.

4 Experimental Method

The following section contains information on the experimental setup used, reasoning behind certain experimental decisions, as well as information on the experimental procedure followed in gathering backup bearing degradation data.

4.1 Experimental setup specifications

Results are obtained through the use of a small scale active magnetic bearing setup shown in Fig. 3. The rotor has a mass of 7kg and deep groove ball bearings (61806) with an air-gap radius of 250 μ m are used as backup bearings.

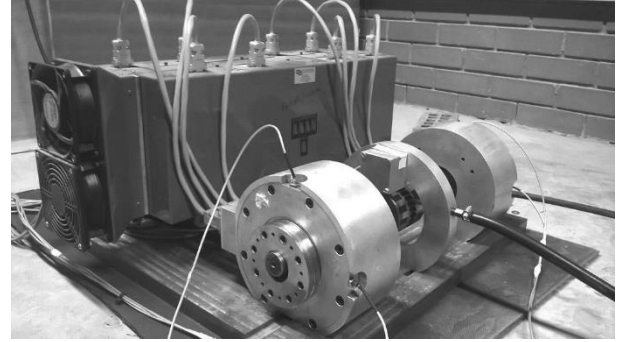


Fig.3: Small scale experimental setup used for experimental testing.

The backup bearings are tested free of any lubrication as to negate the effect of temperature increase on lubrication viscosity and are cleaned by submerging them within a heated ultrasonic bath at 40°C for 30 minutes.

4.2 Experimental procedure

By performing numerous rotor delevitations at the same initial conditions, backup bearing degradation data is obtained. The rotor is levitated and spun up to a speed which is 1000 r/min higher than that of the delevitation speed and allowed to freely spin down and delevitate at a specific speed and angle from the geometric centre of the AMBs. The $Dval$ values for each delevitation is logged and compared, which gives an indication of any changes in the BBs. Through experimental testing, the $Dval$, $Vval$ and $AVval$ values have been found to be very sensitive to changes in BB characteristics which in turn has been found to be directly influenced by the quality and health of the BB system.

5 Experimental Results

In this section, backup bearing degradation due to the multiple rotor delevitations is discussed using $Dval$, $Vval$ and $AVval$. This section contains three separate BB degradation data sets from which two were done at rotor drop down speed of 4500 r/min, and one at 3000 r/min.

5.1 4500 r/min delevitation results

Fig. 4 shows the $Dval$ plots for a bearing upon which catastrophic failure had occurred after 13 consecutive drops.

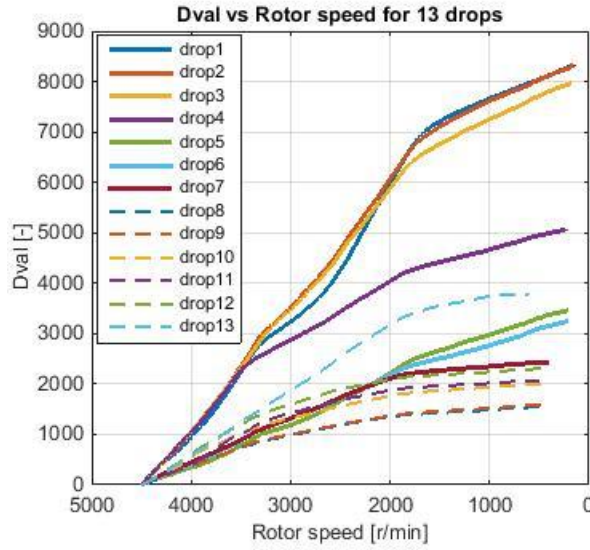


Fig.4: Dval vs r/min of 13 drops at 4500 r/min delevitation speed (Left bearing)

From Fig. 4 we find that the calculated $Dval$ values vary widely between successive drops. This serves as an indication that bearing degradation is taking place since similar experiments at different initial conditions have shown the $Dval$ value to remain constant if no degradation or changes in backup bearing characteristics occurs. By plotting the $Dval(k)$ value to its corresponding drop number found in Fig 4, it highlights these changes and is shown in Fig 5.

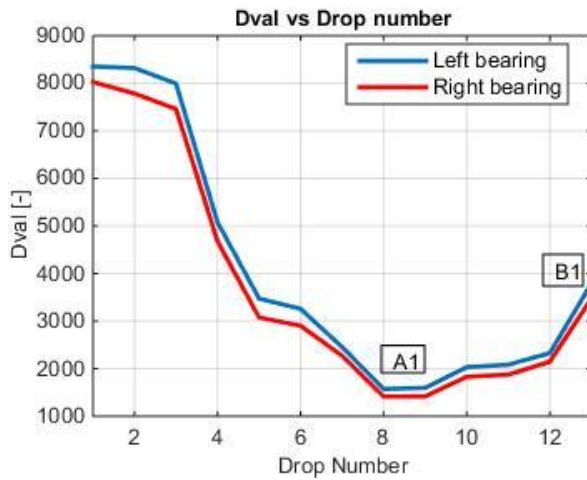


Fig.5: Maximum Dval vs drop number at 4500r/min delevitation speed

In Fig. 5 we find a steady decline in the $Dval(k)$ value between drop 1 and 8. This can be attributed to bearing degradation and deformation of the bearing cage occurring,

where in this case, the deformation causes contact between the bearing cage and the inner/outer race, forcing the bearing to stop within a shorter amount of time creating less movement within the BB clearance. As the bearing cage wears due to contact with the inner/outer race, we find that the $Dval(k)$ value steadily climbs from point A1 up to a point of catastrophic failure at point B1. The steady increase from A1 to B1 is attributed to a lower breaking torque as the cage wears. By plotting the calculated $Vval(k)$ values of each rotor drop as found in Fig 5, a more clear indication on the severity of the corresponding rotor drop can be found. This is shown below.

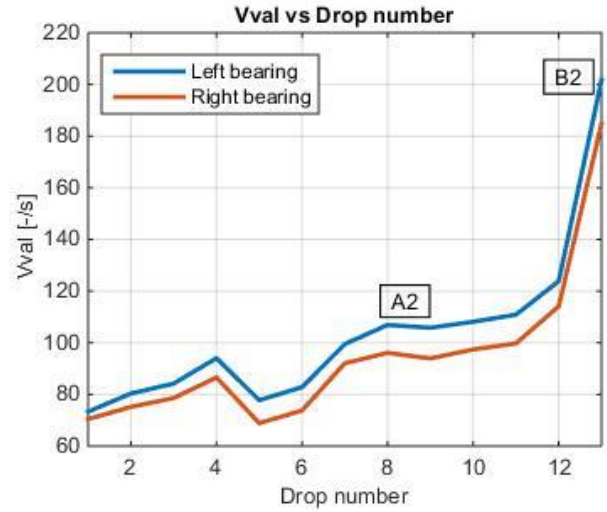


Fig.6: Vval vs drop number at 4500 r/min delevitation speed

In reference to Fig 6, we find that there is an upwards trend of the $Vval(k)$ value between drop 1 to 13. This can be attributed to increased deceleration occurring as the bearing degrades, where sharp or sudden peaks within the $Vval(k)$ plot give some indication towards the severity of certain rotor drops. The sudden increase from drop 12 to 13 shows a clear indication that bearing failure had occurred where in this case, the sharp increase in the $Vval(k)$ value was caused by catastrophic failure of the bearing cage, resulting in sudden deceleration of the bearing and yielding a large $Vval(k)$ value. The figure below shows the $AVval(k)$ plot for the bearing discussed.

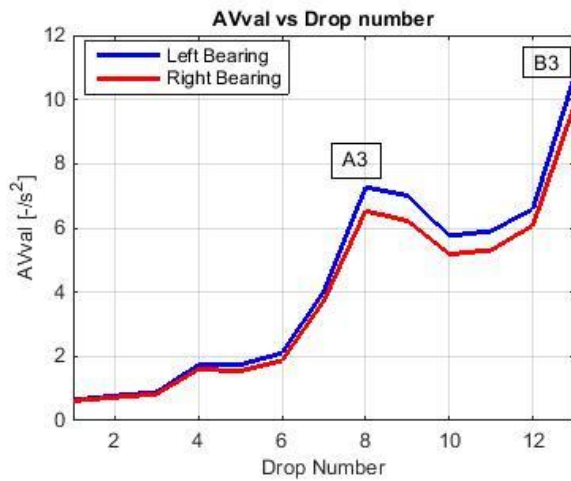


Fig.7: V_{val} vs drop number at 4500 r/min delevation speed

By plotting the calculated $AV_{val}(k)$ values to its corresponding drop number, an upward trend of the $AV_{val}(k)$ vs drop number plot similar to that of the $V_{val}(k)$ plot can be found. This upward trend can once again be attributed to bearing degradation where the sudden spike at B3 shows that the bearing experienced a catastrophic failure. Similar results have been found on other sets of backup bearings where Fig. 8 shows the $D_{val}(k)$ value of separate bearing degradation data sets generated using two sets of bearings.

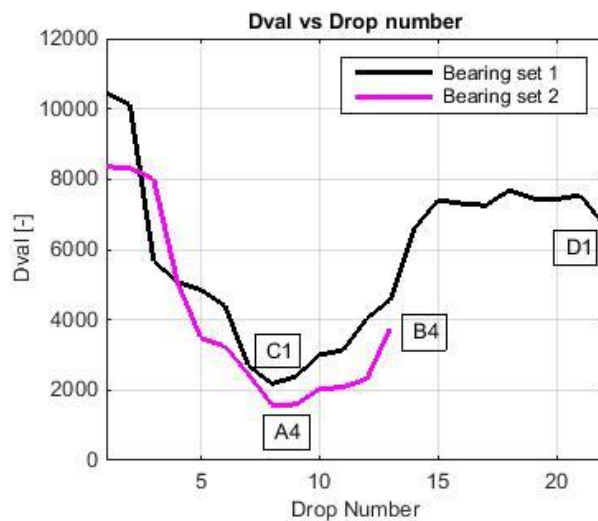


Fig.8: Results comparison between bearing failure after 13 drops, and bearing after 22 drops

From Fig. 8 we find that the two bearing degradation sets yield similar graph shapes. Catastrophic bearing failure for the separate sets of backup bearings occurred at point B4

and D1. The reason why catastrophic bearing failure of the two BB data sets differ, can be attributed to what happens at Point A4 and C1. As explained earlier, contact between the bearing cage and the inner/outer race occurs. Once the bearing cage starts to wear away from point A4 and C1 onwards, debris caused by this wear could either enter the bearing race way, or clear the area as to avoid any obstruction. If debris were to enter the bearing race way, there is an increased chance of catastrophic bearing cage failure occurring. These results were supported by visual inspection on a set of BBs where large pieces of debris (metallic shavings) were found within the bearing raceway just before catastrophic bearing failure had occurred. Fig. 9 shows electron microscope imagery of scratches found within the bearing inner race due to contact with the bearing cage, further confirming that contact does occur between the bearing cage and the inner race. It also shows debris found within the bearing raceway before catastrophic failure had occurred.

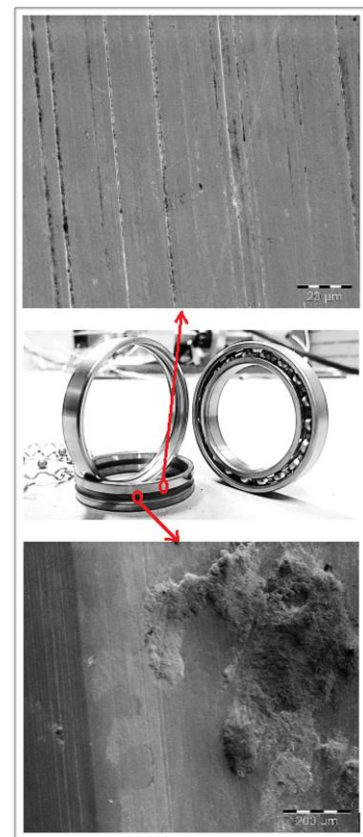


Fig.9: (Top) Scratches within bearing inner race due to contact with bearing cage, (Bottom) Debris located within bearing raceway

5.2 3000 r/min delevitation results

As expected, by changing the initial condition of the rotor drop speed to 3000r/min (under the second critical frequency), the life of the BB is increased to 97 drops until catastrophic failure occurred. The orbit plots for these delevitations are shown in the figure below.

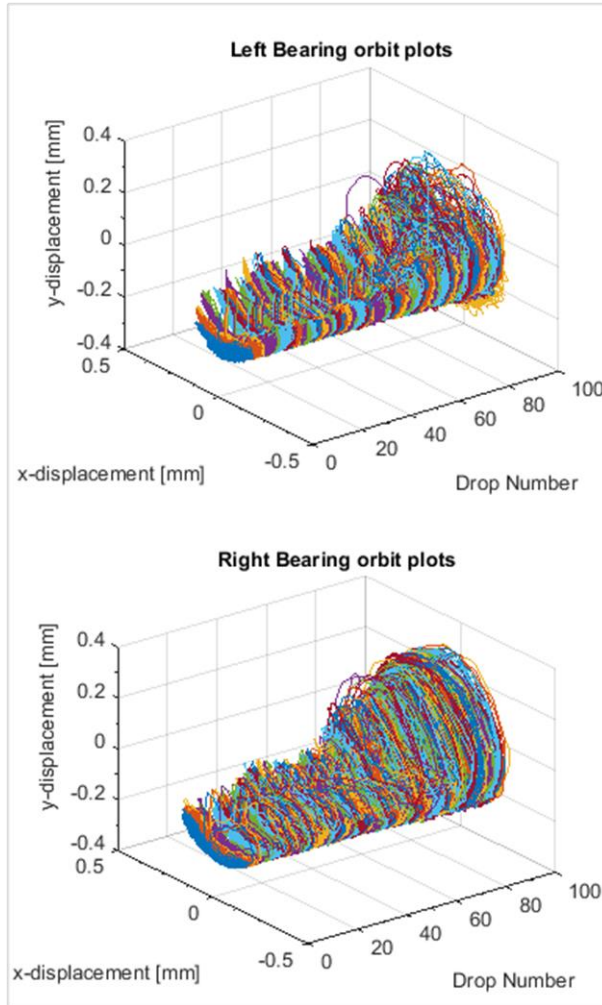


Fig.10: Effect of degradation on backup bearing performance due to repeated delevitations at 3000 r/min.

From Fig. 10 we find that the amount of forward whirl within the BB clearance increases as the drop number increases. Indicating that drop severity increases as the bearing degrades. By calculating and plotting the $Dval$, $Vval$ and $AVval$ value against its corresponding drop numbers (Fig. 11-13), a more clear indication of the above mentioned is found.

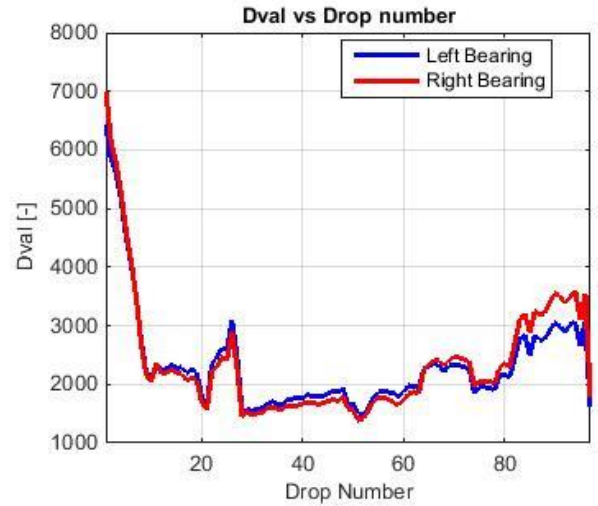


Fig.11: Maximum $Dval$ vs drop number at 3000r/min delevitation speed

Fig 11. shows that the $Dval(k)$ value sharply decreases within the first few drops before increasing. Locations where large decreases within the $Dval(k)$ plot occurs indicates, as discussed in section 5.1, areas where cage deformation causes contact between the cage and the inner/outer race, yielding a lower $Dval(k)$ value. An upward trend indicates degradation and areas where obstructing contact is reduced through wear of the cage. By plotting the $Vval(k)$ values, an indication towards the severity of specific RDEs can be found.

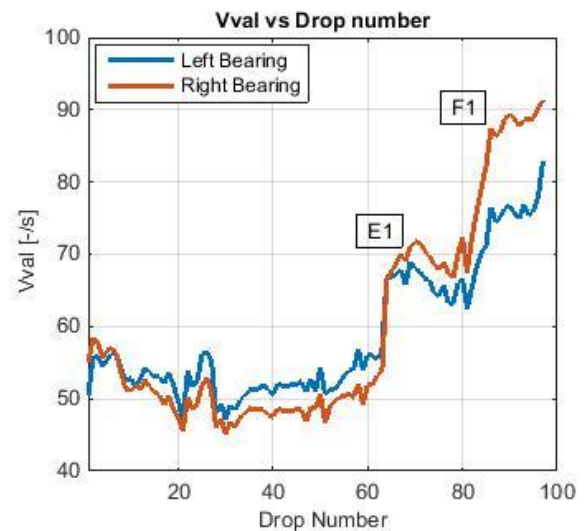


Fig.12: $Vval$ vs drop number at 3000 r/min delevitation speed

In comparison to the 4500r/min results (Fig.6), the $Vval(k)$ plot shown in Fig. 12 does not

clearly show an upward trend throughout the bearing life. It does however once again clearly reveal the location at which the most severe delevitations had occurred (E1 and F1). When referring back to equation 2, we find that $Vval(k)$ is dependent on time, thus the increased $Vval(k)$ values can be attributed towards an increased amount of transverse movement being developed within a shorter amount of time. If compared to Fig. 10, this increased $Vval(k)$ value can directly be linked to the increased forward whirl developing at E1 onwards. It is also interesting to note that a larger increase in $Vval(k)$ appears on the left side bearing at the final drop where failure had occurred. Fig. 13 shows the $AVval$ plot for the bearings discussed.

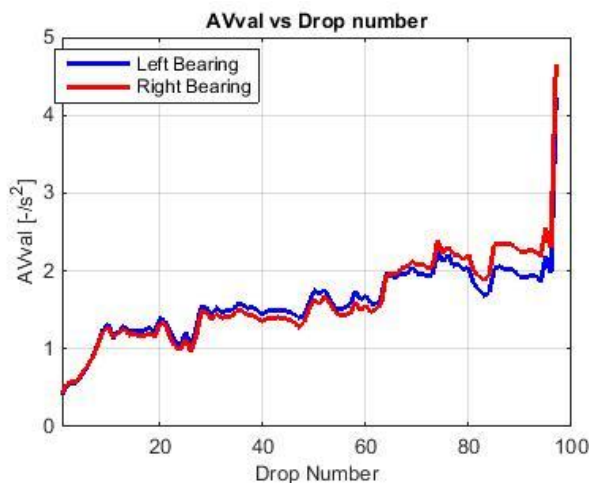


Fig.13: $AVval$ vs drop number at 3000r/min delevitation speed

By plotting the calculated $AVval$ values to its corresponding drop number, a clear upward trend of the $AVval$ plot can be found. This upward trend can be attributed to bearing degradation where the sudden spike within the $AVval$ plot clearly highlights the drop at which catastrophic bearing failure had occurred.

5. Conclusion and future work

Through experimental testing it is found that delevitation severity indicator $Dval$, $Vval$ and $AVval$ gives an indication towards changes within BB system characteristics. It is found that $Dval$ is more suited for monitoring backup bearing performance at a specific drop instance, where $Vval$ is more suited for

monitoring rotor drop severity and shows potential in use for bearing failure prediction. $AVval$ was found to increase over time, giving a more clear indication of BB degradation. The combination of the individual characteristics of $Dval$, $Vval$ and $AVval$ shows some promise for effective real time condition monitoring and possible backup bearing lifetime prediction capabilities. Up to this point, not enough backup bearing degradation data has been obtained in order to develop a backup bearing lifetime prediction procedure. Further investigation is required into the applicability of using these quantification methods for predicting BB failure. Future work includes further experimental testing using a wider range of backup bearing types and sizes with an increased refinement in the experimental method. Upgrades to the experimental setup to be done includes force transducers and accelerometers. This paper serves as a proof of concept showing that severity indicators change as the bearing degrades.

References

- [1] J. J. Janse van Rensburg, "Delevitation modelling of an active magnetic bearing supported rotor," Potchefstroom, 2014.
- [2] G. Schweitzer, "Safety and Reliability Aspects For Active Magnetic Bearing Applications - A Survey," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 219, no. 6, pp. 383-392, 2005.
- [3] G. Sun, "Auxiliary Bearing Life Prediction Using Hertzian Contact Bearing Model," *Journal of Vibration and Acoustics*, vol. 128, no. 2, pp. 203 - 209, 9 September 2005.
- [4] J. G. Lee, "A Nonlinear Transient Approach For Morton Synchronous Rotordynamic Instability And Catcher Bearing Life Prediction," Texas A&M University, 2012.
- [5] T. W. Reitsma, "Development of Long-Life Auxiliary Bearings for Critical Service Turbomachinery and High-Speed Motors," in *Proceedings of the 8th International Symposium on Magnetic Bearing*, Mito Japan, 2002.
- [6] J. J. Janse Van Rensburg, G. Van Schoor and P. A. Van Vuuren, "Delevitation Modelling of an Active Magnetic Bearing Supported Rotor," in *Proceedings of the 12th International Symposium on Magnetic Bearings (ISMB12)*, Wuhan China, 2010.

Appendix E. Electronic attachment

The calculations and delevitation results presented within this dissertation can be found on the attached disk. Due to the size of the rotor delevitation results (120 GB), only some of the results are presented. The full delevitation results can be made available through cloud storage and online sharing sites. Contact 21662428@nwu.ac.za or Jan.JanseVanRensburg@nwu.ac.za for more information regarding the above mentioned.