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

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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 (*ΔDVAL*).

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.

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

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.

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

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.

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

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.

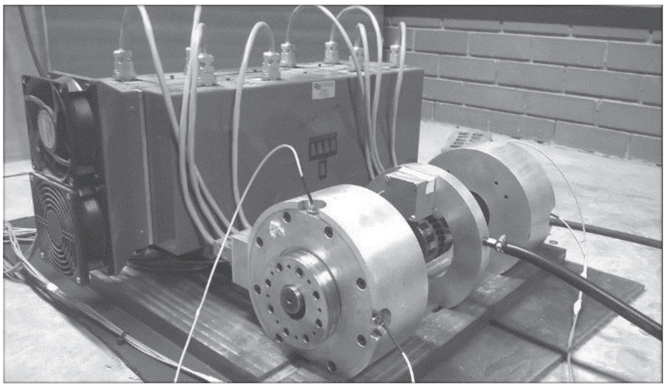

Fig. 1 AMB system used to gather BB degradation data

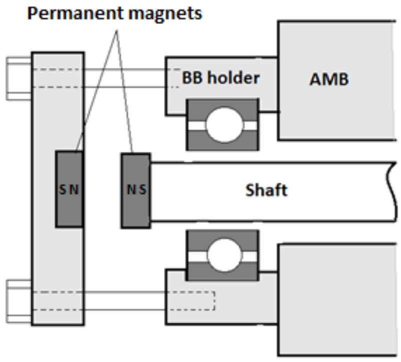

Fig. 2 Simplified sketch of BB system assembly

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.

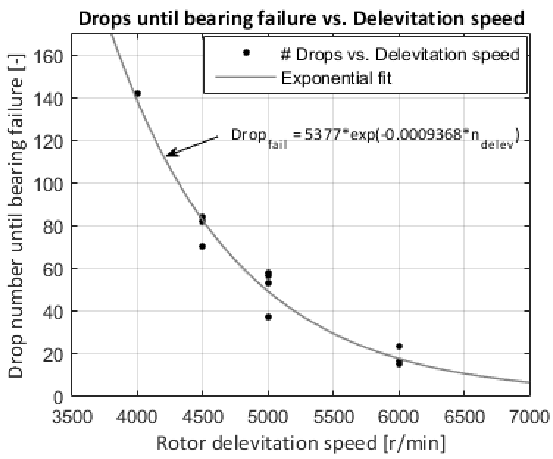

Fig. 3 Number of RDEs until failure

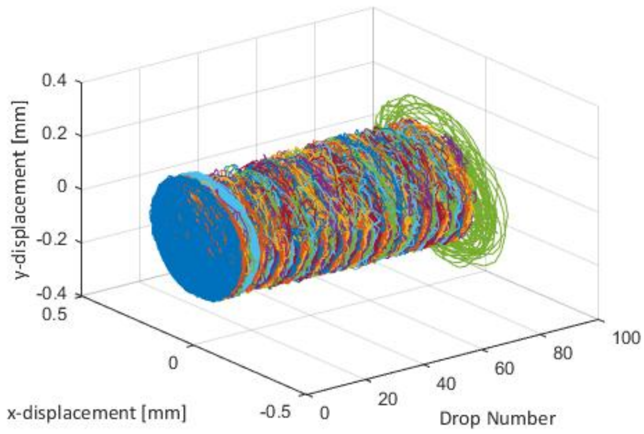

Fig. 4 Orbit plots for multiple 4500 r/min RDEs

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.

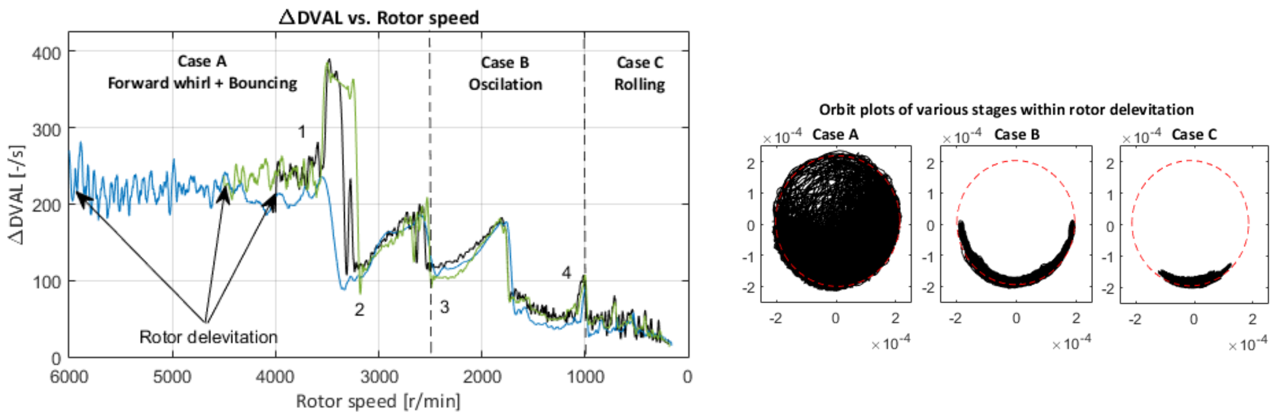

Fig. 5 Rotordynamic response analysis using Δ*DVAL*

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.

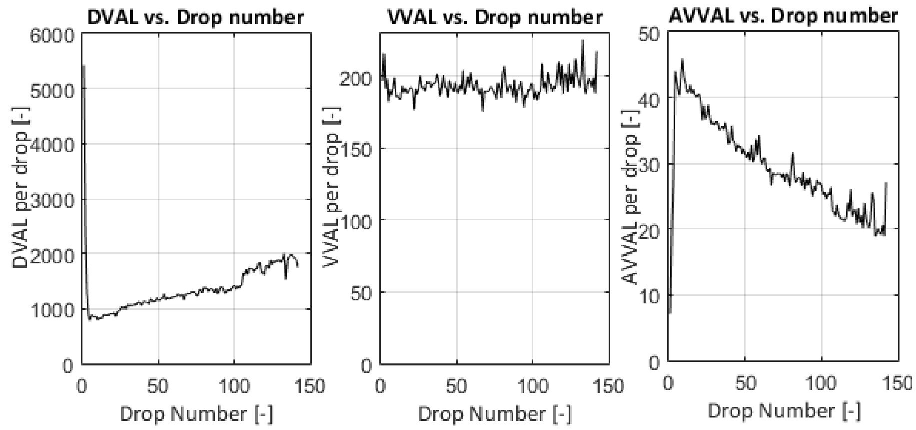

Fig. 6 142 delevitations at 4000 r/min quantified using *DVAL*, *VVAL* and *AVVAL*

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. Figure 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. Figure 7 (right) shows the failure zone. The failure zone line is based on the statistical distribution of failure for all of the BB sets.

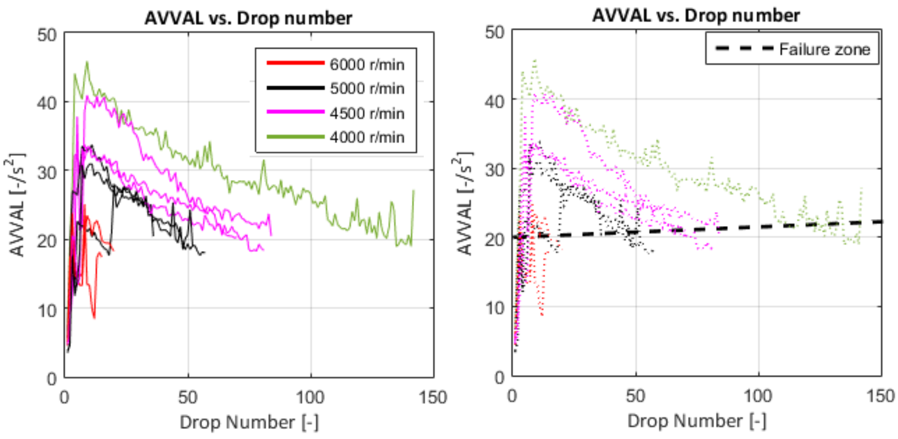

Fig. 7 Failure zone obtained from quantifying degradation for multiple delevitation conditions

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.

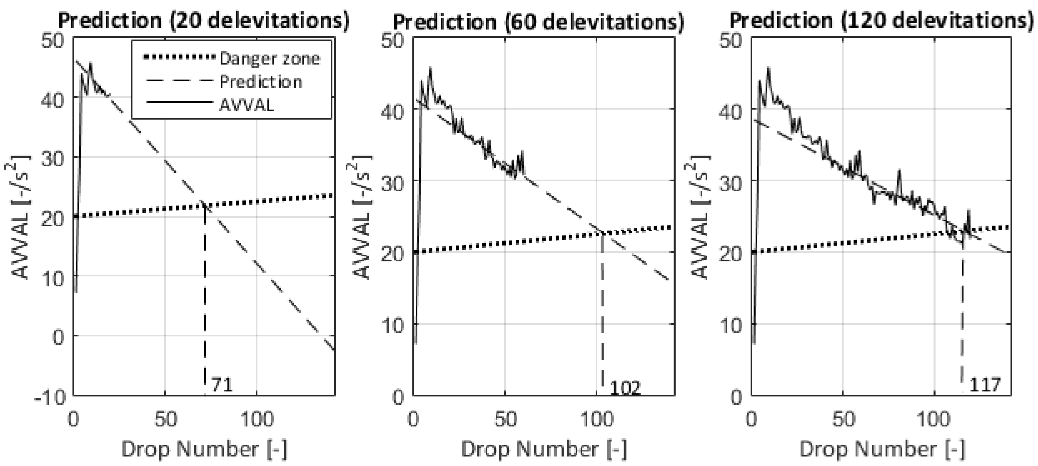

Fig. 8 Delevitation severity indicator in BB life prediction example

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 *ΔDVAL*, 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.

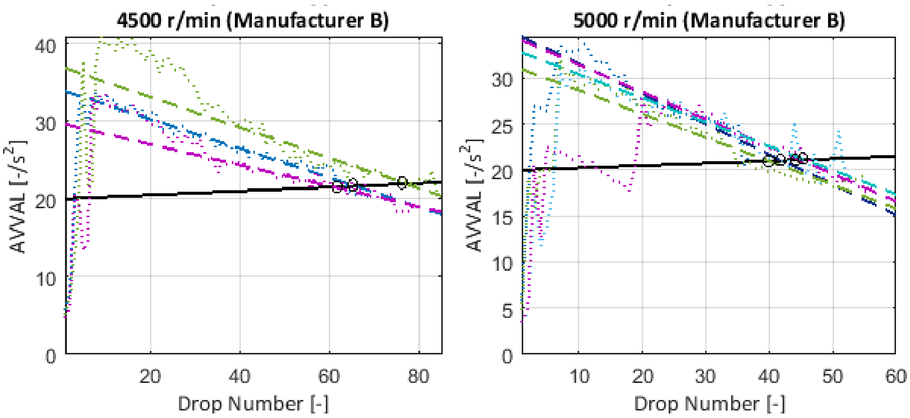

Fig. 9 Delevitation severity indicator life prediction validation

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 1 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 *ΔDVAL*. 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

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