BACKUP-BEARING LIFETIME PREDICTION USING QUANTIFIED DELEVITATION SEVERITY INDICATORS

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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.

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

Another method, in which the severity of an RDE can be measured, is the average non-dimenionalised 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.

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

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.

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

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.

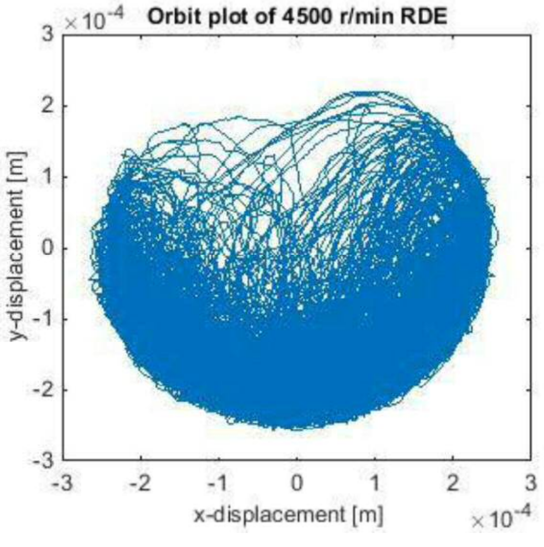

Fig. 1: Orbit plot of 4500 r/min Delevitation

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

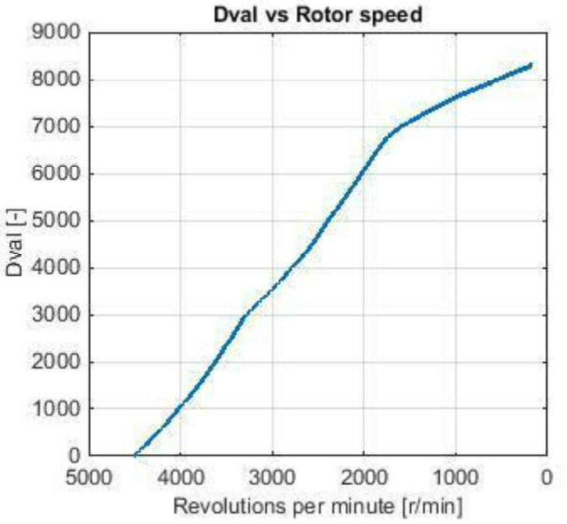

Fig. 2: 4500 r/min Delevitation Quantified using *Dval*

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 250µm are used as backup bearings.

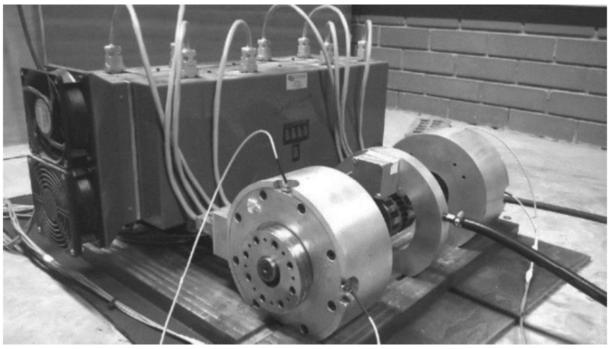

Fig. 3: Small scale experimental setup used for experimental testing.

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.

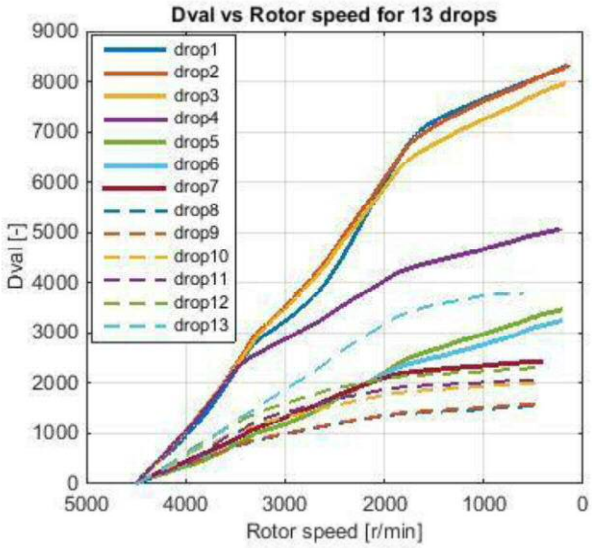

Fig. 4: Dval vs r/min of 13 drops at 4500 r/min delevitation speed (Left bearing)

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.

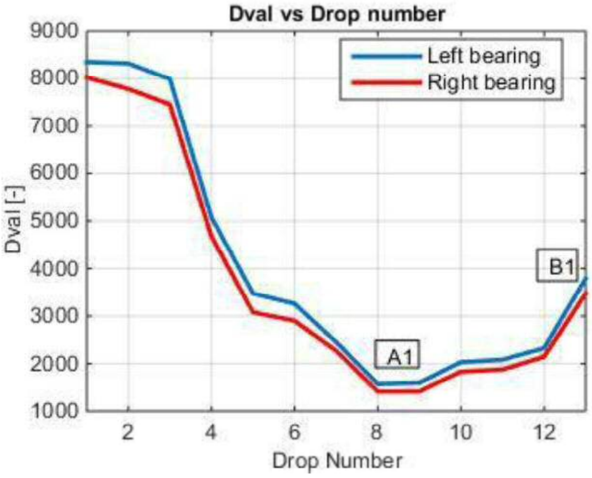

Fig. 5: Maximum Dval vs drop number at 4500r/min delevitation speed

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.

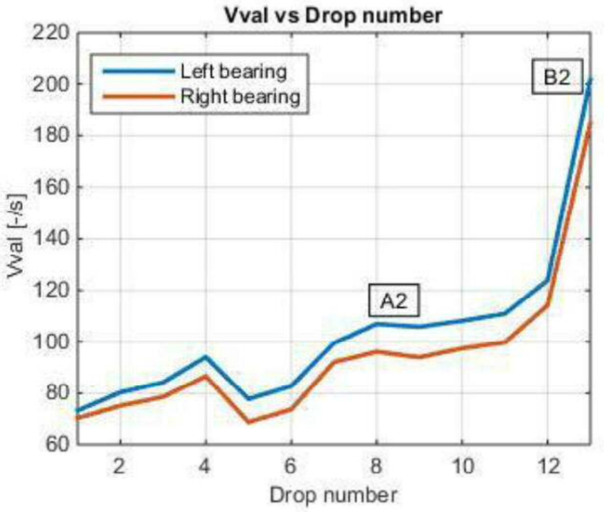

Fig. 6: Vval vs drop number at 4500 r/min delevitation speed

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.

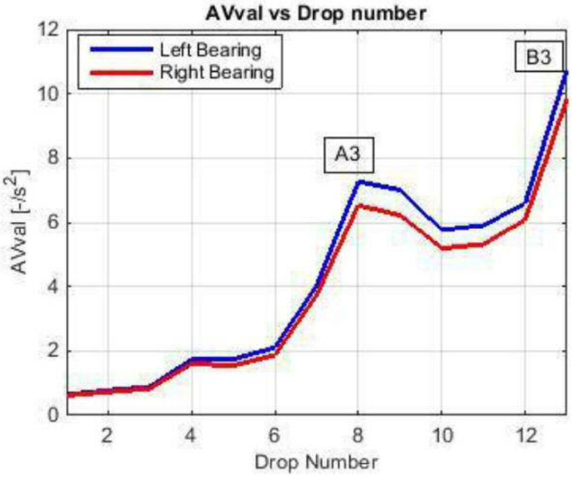

Fig. 7: Vval vs drop number at 4500 r/min delevitation speed

By plotting the calculated *AVval(k)* values to its corresponding drop number, an upward trend of the *AVval(k)* vs drop number plot similar to that of the *Vval(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 *Dval(k)* value of separate bearing degradation data sets generated using two sets of bearings.

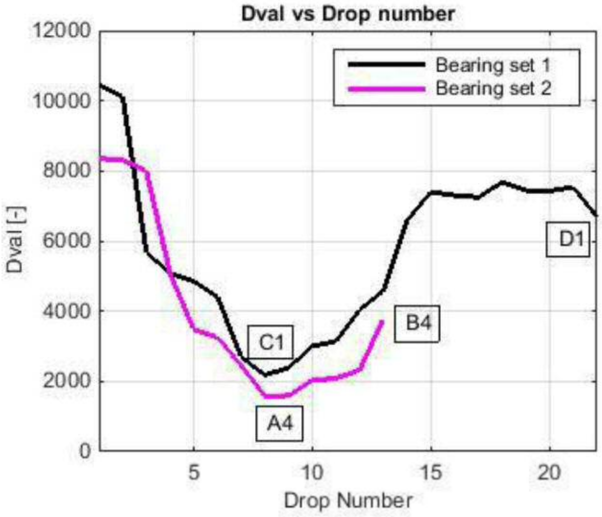

Fig. 8: Results comparison between bearing failure after 13 drops, and bearing after 22 drops

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.

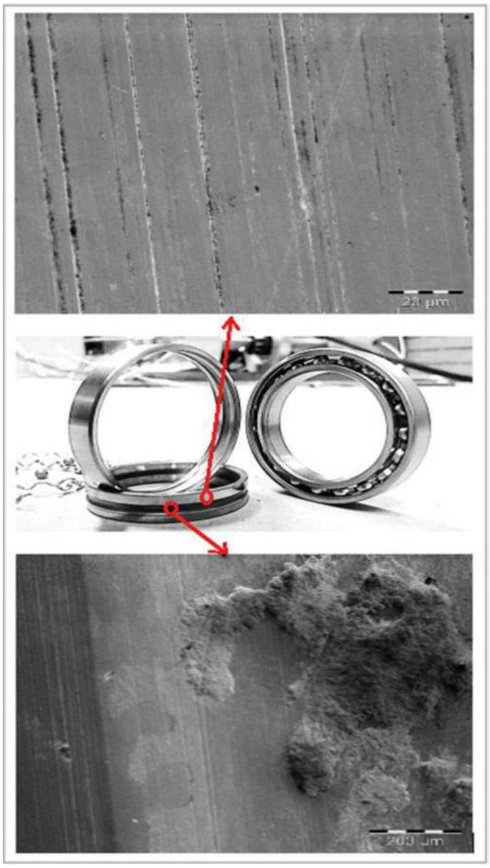

Fig. 9: (Top) Scratches within bearing inner race due to contact with bearing cage, (Bottom) Debris located within bearing raceway

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.

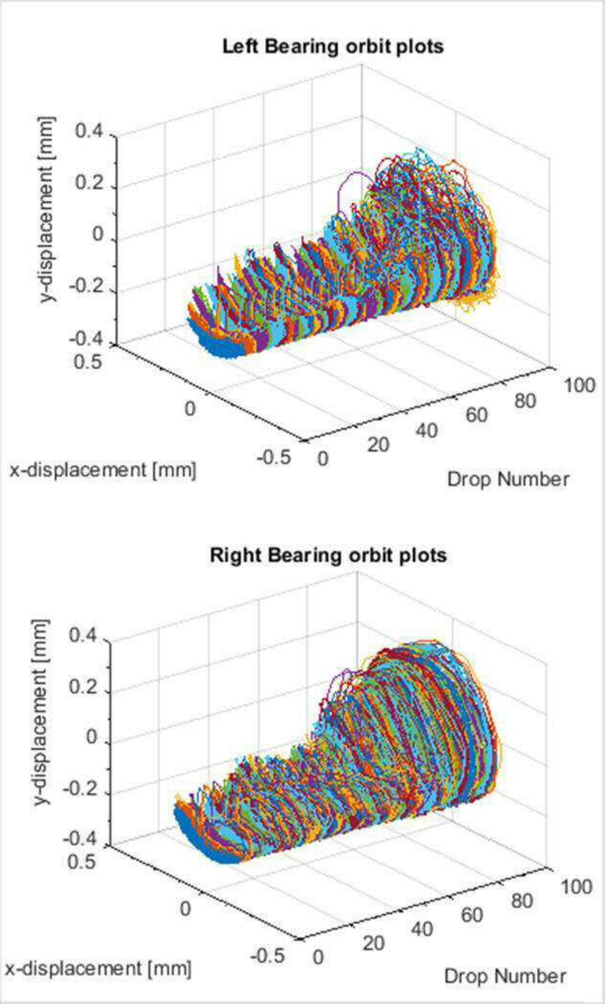

Fig. 10: Effect of degradation on backup bearing performance due to repeated delevitations at 3000 r/min.

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.

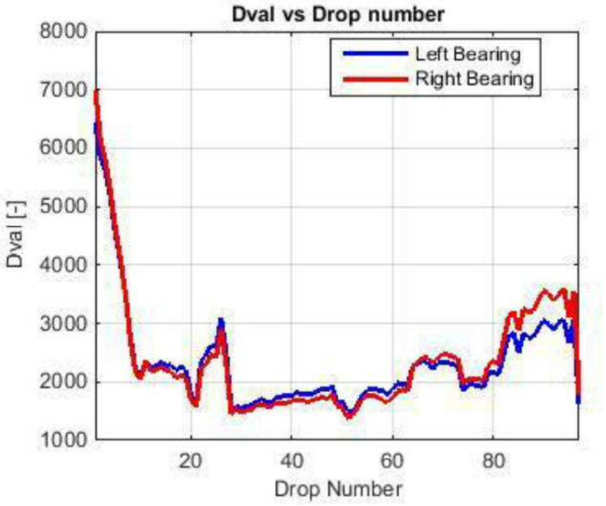

Fig. 11: Maximum Dval vs drop number at 3000r/min delevitation speed

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.

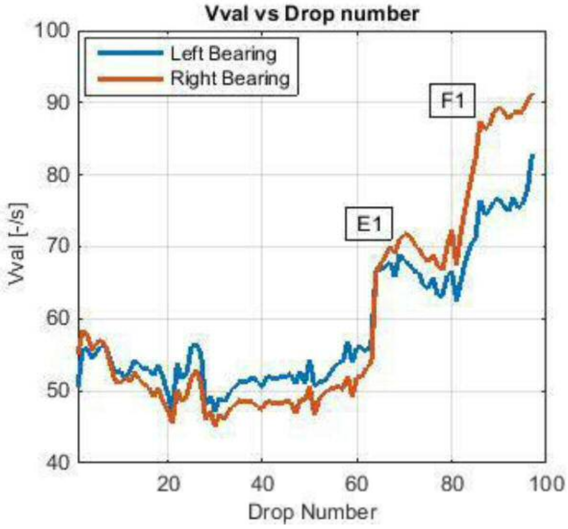

Fig. 12: Vval vs drop number at 3000 r/min delevitation speed

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 occured (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.

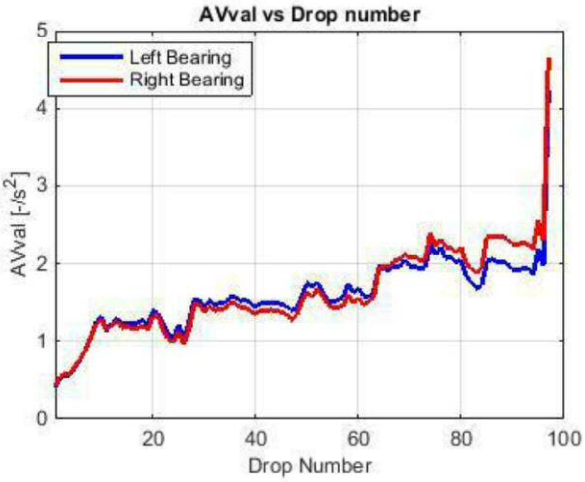

Fig. 13: AVval vs drop number at 3000r/min delevitation speed

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

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