COMPARISON OF DUCT-MOUNTED VIBRATION AND INSTANTANEOUS AIRGAP TORQUE SIGNALS FOR PREDICTIVE MAINTENANCE OF VANE AXIAL FANS

D. Doan
ddoan1@txu.com
Texas Utilities

E. Wiedenbrug, SM IEEE
wiedenbrug@ieee.org
Baker Instrument Company

Abstract: Vane axial fans find frequent applications in nuclear environments. Their failure can result in unplanned outages, health and safety costs and extensive damage to supplementary equipment. The preferred method of diagnosis, vibration measurements on the bearing's housing, cannot take place due to the fact that these fans are mounted inside of ducts. This paper shows the results obtained in a controlled laboratory environment in which two different field friendly predictive maintenance methods were compared. The first investigated method is connecting accelerometers to the outside of the duct in which the fan is mounted. The second method is investigating the instantaneous airgap torque as calculated via Park's vector theory. Frequency components of the signals were compared during baseline and faulted conditions of the fan. Two cases, unbalanced load and a fault in the outer race of the bearing were diagnosed with the both sets of field friendly instrumentation. This investigation's results show promise to change the way in which Predictive Maintenance is performed for these loads in the near future.

Key words: Motor Diagnostic, Bearing Failure, Unbalance, Vane Axial Fan.

I. INTRODUCTION

The ability to detect failure modes and plan maintenance is the purpose of a reliability centered maintenance concept. Safety, health and low operating costs depend upon an early detection of load deterioration, allowing timely maintenance prior to catastrophic failure.

Vane axial fans supply and exhaust air at higher pressures and greater flow rates than squirrel cage fans, and so find frequent applications in the nuclear power industry. They are typically mounted horizontally or vertically inside of the air stream, and mounted to the air ducting through diffusers on one end and a support plate or rods at the other end as seen in Fig. 1.

Commonly, the standard method of detecting rolling-element bearing failures is by attaching an accelerometer to the bearing housing or near the load zone of the bearing. An in-duct mounted fan presents a barrier to applying such predictive maintenance tools to monitor the condition of the motor and fan rotating components. The closest point of attachment of accelerometers in the field is the outside of the duct. Assessing the quality of the obtained signals from duct-mounted accelerometers is one part of the investigation presented here.

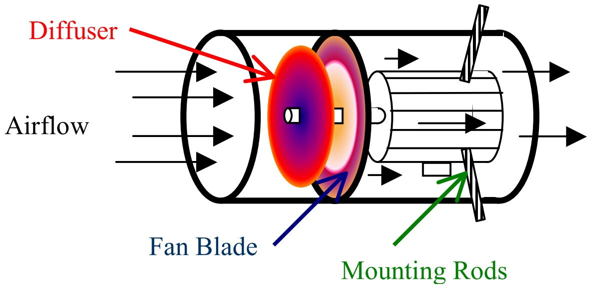

Figure 1: Horizontal Vane-Axial Fan.

Casada et al [1] exposed the concept of using an induction motor as a sensor to its own driven load. Current signature analysis and power signature analysis have been implemented to monitor motor operated valves (MOVs) since 1996. Riley et al [2] showed that the vibration to which a motor is exposed can be found modulated in the frequency domain data of the stator currents. The instantaneous torque signal (ITS), is, in its nature demodulated. It can be calculated with Park's vector as described in [3] was used in [4] for predictive maintenance purposes in a fossil generation plant, by analyzing it in the time domain.

The second goal of this paper is to investigate the diagnostic value of the ITS for diagnosis of vane axial fans. ITS was transformed into a frequency domain spectral signal of the torque. Baseline measurements were compared to measurements taken after faults were planted. The faults reported in this paper are two different cases: mechanical load unbalance on one hand and an outer bearing race fault on the other.

II. LABORATORY SETUP

A. Testing Equipment and Setup

In a laboratory setup, a 5hp driven 4-pole Baldor motor was tested with a 24-inch fan manufactured by Aerovent. The fan utilized is a model representative of those used in the Comanche Peak Steam Electric Station to exhaust air from the Electric Control Buildings. It was chosen because the internal support system has a long transmission path between motor bearings and the external duct. This can possibly dampen the bearing's vibration signal and potentially compromise the predictive maintenance measurements if taken from the outside of the duct. Fig. 2 depicts the fan utilized in this test.

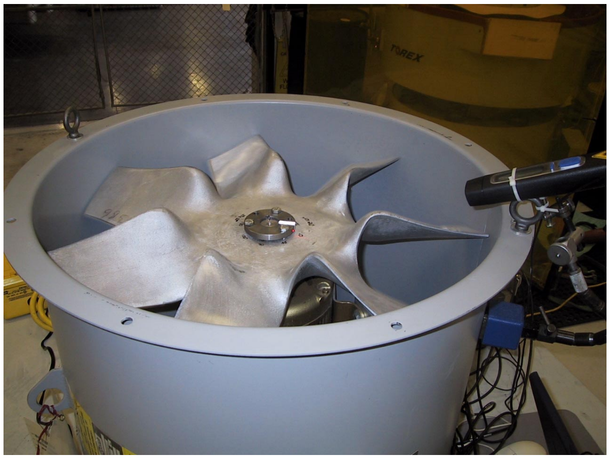

Figure 2: 24-inch vane-axial fan.

A variety of vibration analyzers were used to verify the measurements. A Cognitive Systems CV395B spectrum Analyzer, a Bentley Nevada ADRE 208P (Automated Diagnostics for Rotating Equipment) and a SWANTECH stress wave analysis system. Additional instrumentations used in parallel to the vibration instruments were air flow meters, accelerometers, laser tachometers, current meters, thermocouples, multi meters and a humidity meter.

Figure 3: Fan cowling vibration transducers.

B. Investigated Instrumentation

The vibration detectors were all 100mW/g ICP transducers, installed on the fan duct as seen in Figs 3 and 4. An additional set of 4 accelerometers was installed onto the motor. This set of accelerometers was only used to verify balancing and the severity of the planted fault modes. Motor-mounted accelerometers are too intrusive for field use hence they were not evaluated for the testing performed here.

The ease of use of instrumentation in the field is vital for any predictive maintenance program. Installing torque transducers is a prohibitive expense if all critical loads are to be monitored. The tool that was used to evaluate the ITS was Baker Instrument Company's Explorer. Three clamp-on current sensors were monitoring the currents to the motor, while 3 voltage clips were connected to the terminals. These sensors are connected to a safety and conditioning unit, which performs the data acquisition, processing and display of the results. The equipment is designed to be operated at the motor control centers; either directly connected to low voltage motors or hooked to the secondary of the PTs and CTs that are used for relaying, in case of voltage levels higher than 600V.

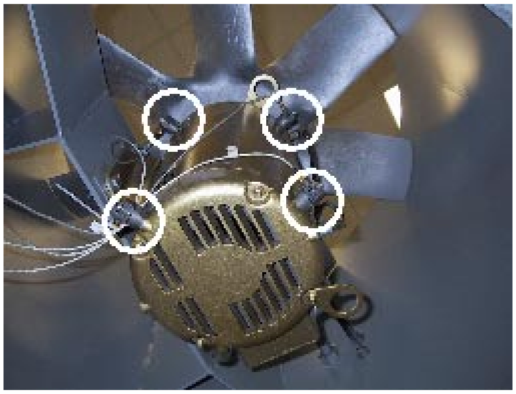

Figure 4: Motor bearing housing transducers

The equations used for airgap torque calculations are the standard *dq* equations in the static reference frame, as specified in [3]. The result is an instantaneous torque signal. Both types of faults evaluated here are diagnosed in the frequency domain. The frequency spectrum of the ITS is calculated, so that the particular frequency components of the torque signal can be compared to the frequency components of the different vibration components. Fig. 5 shows an example of the spectral information offered by the ITS tool.

III. TESTING PROTOCOL

The testing was divided into 3 sections and each section had data from 2 different sets of sensors. First, data was taken on a well-aligned and balanced load. The second portion of the testing was done after an imbalance was introduced. For the third test, the load bearing was exchanged for one with a planted fault, and the load was balanced. All three conditions were measured using simultaneous data collection of the motor's electrical signature (ITS) and duct vibration.

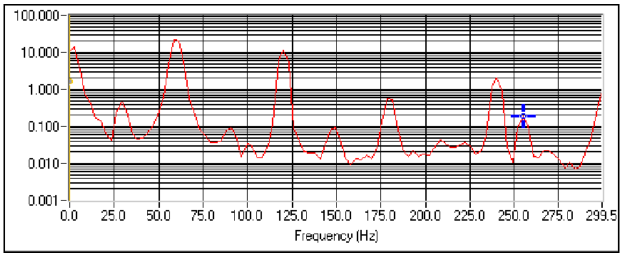

Figure 5: Torque spectrum (Nm) versus frequency (Hz)

A. Imbalance test:

An imbalance of 7.6 grams was introduced to the fan-jacking bolt at 2 inches from the center of the fan, resulting in an imbalance of 0.54 ounce inches. This created an eccentric unbalance doubling the vibration in inches per second at the motor outboard bearing. Fig. 6 shows the attached imbalance from a top view of the fan, with the balancing weight attached to the bolt to the bottom right, the imbalance weight attached to the top bolt, and the fan bolts evenly distributed at 120° around the shaft.

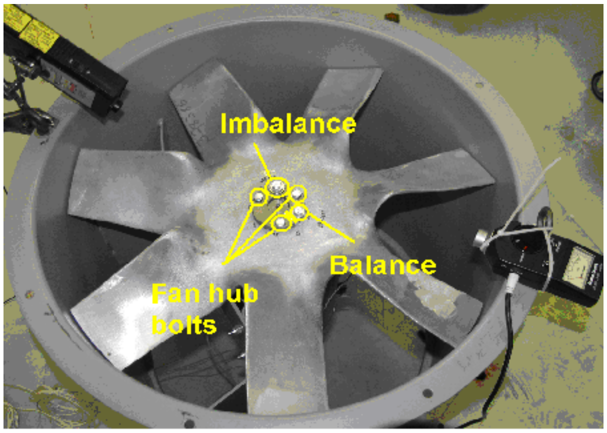

Figure 6: Fan, hub bolts, balance weight, 7.6g of imbalance weight.

The energy of the 1x rpm vibration (also known as the fundamental speed frequency) is commonly used to monitor an increased imbalance. This is the frequency band of interest that has been investigated both sets of sensors, the duct mounted accelerometers and the ITS measured at the motor control cabinet (MCC).

B. Bearing Outer Race Fault

A bearing with a half-inch long, 1/16 in deep and 1/16 inch wide groove was inserted onto the shaft at the fan end of the motor. Figure 7 shows the sample, which was cut and prepared after the testing was completed:

A groove in the outer race will show at the frequencies specified in (1), as shown in [5]

$$Outer\ Race\ (BPFO) = \frac{n}{2} f\left(1 - \frac{Bd}{Pd} Cos\beta\right) \qquad (1)$$

Where BPFO stands for Ball Pass Frequency Outer race, n is the number of balls of the bearing, f is the rotating speed in Hz, Bd is the Ball diameter, Pd is the Path diameter (average between inner and outer race diameters), and β is the contact angle. The *BPFO* calculates for this bearing to 107Hz, and was the frequency of interest monitored for both sets of sensors.

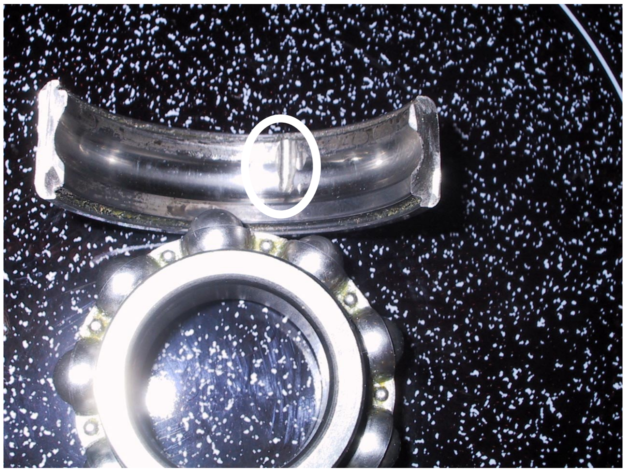

Figure 7: SKF® 6503 deep groove bearing

C. Statistical Evaluation

Due to the nature of the performed test, and the variation of the measurements taken with the motor-mounted accelerometers during the baseline test, it became apparent that a statistical evaluation was necessary. The method chosen for this evaluation is the method of the single sided t design. The method and background to the design of this experiment is explained in detail in [6-7]. Minimal number of samples, as a function of standard deviation of the samples and requested power of the test were calculated according to

$$N_{pairs} = \left(U_\alpha + U_\beta\right)^2 \frac{\sigma_{diff}^2}{\delta_{diff}^2} \qquad (2)$$

where N_{pairs} is the number of trial pairs, U_α and U_β are the standard normal deviations associated with type I and type II errors, and σ_{diff}^2 and δ_{diff}^2 are the differences between the two means that are important from an Engineering viewpoint. The chosen values for α and β were the industry's common choices of 0.05, and 0.10 respectively. This means that the likelihood of a type I error with respect to the null hypothesis, stating that there is a statistically relevant difference between the samples whereas there really was not, is of less than 5%. This translates into a power of the test performed of more than 95%. A type II error, meaning that the alternate hypothesis was not accepted, while it should have been; stating that there was a difference in the samples whereas there really was not, is of less than 10%.

The calculated necessary number of pairs was of 8.6. The chosen number of samples needs to be larger than the number of pairs, and it was chosen to be equal to 11.

The performed statistical evaluation defines whether the comparison of the data shows a statistically relevant difference in the two compared groups of data. The following comparisons were made:

a) 1x vibration comparison of baseline to a mechanically imbalanced condition

b) 107Hz component comparison of baseline to grooved outer race data

These two sets of data were compared independently for both sets of field friendly sensors; the accelerometers mounted externally to the duct (cowling sensors), and the ITS measured from the MCC. Additionally, the accelerometers mounted on the motor were used to perform baseline evaluations of standard deviations with which a minimal number of samples could be estimated prior to testing. The motor mounted accelerometers were also used to verify the influence of the planted failures.

IV. RESULTS

A. Imbalance to Baseline, Bearing Cap

This test investigates whether the introduction of the mechanical imbalance changes the amplitude of the accelerometers mounted on the Bearing Cap. It was used to verify the planted fault and to evaluate the standard deviation of the signatures for the utilized test setup. The frequency component of interest is the 1x rpm component, and the output of the sensor is in Volts.

Table I: Imbalance to Baseline, Bearing Cap

Trial	Baseline 1x	Imbalance 1x
1	0.000835219	0.001401683
2	0.000901405	0.001448703
3	0.000902928	0.001451159
4	0.000923814	0.001451159
5	0.000973325	0.001495948
6	0.000925900	0.001450340
7	0.000925378	0.001402474
8	0.000924857	0.001451159
9	0.000948282	0.001404057
10	0.000924857	0.001451977
11	0.000924857	0.001403266

Table I shows an example of the raw data used for the statistical evaluation. The Imbalance to the Baseline comparison has the special importance that it is also used to verify that the setup shows a statistically relevant difference in the 1x rpm. The comparisons of the other two sensor arrays can then be utilized to verify whether these particular sensors are able to observe an existing difference.

The following statistical evaluations were done according to methods described in [6-7], yet using the software package WINKS rev 4.65.

The results of this test series are the following: It can be said with a certainty of 99% that the baseline amplitudes lie in between 0.00089 and 0.00095, with the median value being 0.00092 and a standard deviation of 1E-4. This compares to a certainty of 99% that the imbalanced case shows amplitudes in between the values of 0.00141 and 0.00147; with a median of 0.00145 and a standard deviation of 3E-5. Dividing the imbalanced case median by the baseline case's, we obtain a gain of 1.58 for the 1x rpm, which displays the amount of increased vibration due to the added imbalance.

The null hypothesis stating that there is no significant difference between both populations is rejected with a p-value below 0.001, and the alternate hypothesis stating that there is a significant difference in the amplitude level for this test is accepted.

B. Imbalance to Baseline, Cowling

This test investigates whether the influence of the added imbalance to the load can be observed as a change in the amplitude of the 1x rpm accelerometer's signal attached to the outside of the fan duct.

The results of this test series are the following: It can be said with a certainty of 99% that the baseline amplitudes lie in between 0.0002871 and 0.0002873, with a standard deviation of less than 1E-7. This compares to a certainty of 99% that the imbalanced case shows amplitudes in between 0.0003062 and 0.0003064 with a standard deviation of less than 1E-7. Dividing both mean amplitudes by each other results in the gain of 1.067.

The null hypothesis stating that there is no significant difference between both populations is rejected with a p-value below 0.001, and the alternate hypothesis is accepted. This means that the difference in amplitudes for this test is observable from the outside of the duct. However, this result is to be viewed with caution since only a 6.7% increase in the signal was observed, which would evade a common predictive maintenance setup in the field. Even though the data is statistically significantly different, it does not display a sufficient increase to be useful as a predictive maintenance tool.

C. Imbalance to Baseline, ITS

This test investigates whether the influence of the added imbalance to the load can be observed as a change in the amplitude of the 1x rpm ITS signal, as measured from the MCC.

The results of this test series are the following: It can be said with a certainty of 99% that the baseline amplitude lie in between 0.00013 and 0.000139, with a standard deviation of 4E-5. This compares to a certainty of 99% that the imbalance case shows amplitudes in between 0.0196 and 0.0209, with a standard deviation of less than 6E-4. Dividing both mean amplitudes by each other results in the gain of 150 or above 40dB, which is a very useable gain for predictive maintenance purposes.

The null hypothesis, that there is no significant difference between both populations is rejected with a p-value below 0.001, and the alternate hypothesis is accepted. This means that both amplitudes are significantly different.

D. BPOR to Baseline, Cowling

This test investigates whether the influence of the scratched outer race on the bearing can be measured by attaching accelerometers to the outside of the duct. The frequency of interest is the BPOR, at 107Hz.

The result of this test series is that the null hypothesis is accepted. There is no significant difference between the signal's amplitude for the baseline and the BPOR case. This means that the accelerometer mounted on the cowling is an unsuitable method to determine bearing degradation.

E. BPOR to Baseline, ITS

This test investigates whether the influence of the BPOR bearing failure mode can be observed as a change in the amplitude to the signal of the ITS.

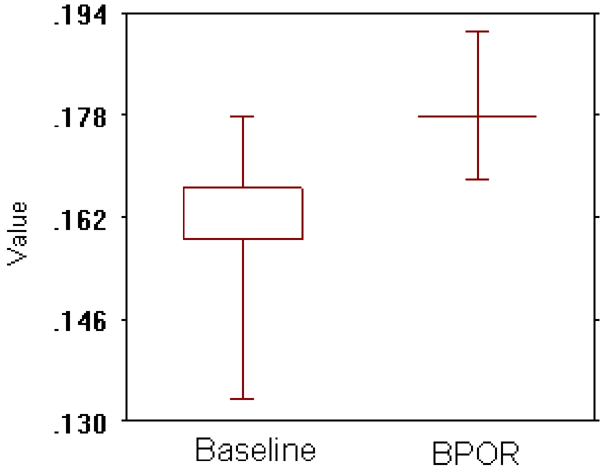

Figure 8: Box and whiskers of baseline and BPOR

The results of this test series are the following: The mean of the Baseline, 0.159, compares to 0.178 for the BPOR case. This represents a gain of 12%. The standard distributions are 0.014 and 0.007 respectively. Fig. 8 is a box and whiskers plot of the two runs, showing that the lowest BPOR value measured lies below the maximal baseline value. Additionally it can be seen that the majority of the measured BPOR values (all values between the 25 and 75 percentiles are of an amplitude similar to the maximal amplitude measured on the baseline. The spread of the measured values displays why a statistical evaluation of the measured amplitudes is required, if BPOR are to be found in a predictive maintenance environment.

The null hypothesis was rejected and the alternate hypothesis was accepted. This means that there is statistically relevant information to show a difference in the amplitudes measured. The p value of this test resulted in p=0.002.

V. CONCLUSIONS

A typical 5hp 4-pole fan application was evaluated regarding possible predictive maintenance methods. The particular challenge that this application poses is that the motor is mounted inside of a duct, and there is no accessibility to it for the common predictive maintenance method of vibration monitoring. Two different fault types were evaluated; a mechanical imbalance of the fan on one hand, and an outer race bearing fault on the other. These fault modes were evaluated for two sets of field friendly sensors. The first set of sensors was the 'Cowling Accelerometer', which was connected to the outside of the duct. This is the closest available point to perform field friendly vibration testing for this 'fan in a can' application. The second set of sensors utilized was an instrument connected at the MCC, which measuring only currents and voltages, calculates the instantaneous torque. The measurements of these two sensors were investigated by looking at the frequency components known to display the early failure modes. These frequencies were the 1x rpm for the imbalanced case, and 107Hz for the BPOR case.

Table II: Summary of Results:

	Cowling Accelerometer	ITS
Imbalance	Observable Very low gain	Observable Very good gain
BPOR	Non observable	Observable Low gain

A summary of the results is given in table II. It displays that the cowling accelerometer is incapable of detecting outer race bearing faults. Moreover it is only marginally useful for detecting imbalances. The reason for this is that the detected rise in amplitude was of only 6.7% compared to the baseline, well-balanced case. In normal field operation, this difference in amplitudes is not sufficient to be noticed by the predictive maintenance operator.

The ITS showed very powerful in identifying mechanical imbalances of the load. It was also able to distinguish the case of the planted bearing failure. The gain for the BPOR test set, however, was 12%. This amplitude gain is useable for day-to-day predictive maintenance, yet lower than optimal in field friendly predictive maintenance. The standard deviation of the ITS BPOR results is large enough as that multiple measurements need to be taken and evaluated statistically for accurate assessments. To date, however, this is the only known field friendly alternative to perform predictive maintenance in this type of application.

The results of this investigation have caused a change in the way predictive maintenance is being performed at this particular nuclear power station. Historically, only the Cowling Accelerometer method was used. Currently, the ITS is viewed as the preferred method and it is being implemented into the standard tool-belt of predictive maintenance.

VI. REFERENCES

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