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Condition-Based Monitoring of Kiln Induced Draft Fan in A Dry Process Cement Plant for Efficient Utilization

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Abstract: Associated downtime and economic loss caused by replacement/maintenance of equipment necessitated pro-active technique known as Condition-Based Monitoring to prevent/reduce failures. This study evaluated the vibration of Kiln Induced Draft (KID) of cement plant before and after failure. Vibration data was acquired using accelerometer probe and data obtained were analyzed statistically by employing t-Test at 95% confidence. Results showed that vibration signals measured in mm/s for KID motor and fan bearings (non-drive and drive ends) in the horizontal plane recorded higher values than vertical and axial planes when measured before failure occurrences. After failures, horizontal plane values increased by more than 120% while those measured in the vertical and axial planes increased by less than 100%, making horizontal plane vibration measurement a more suitable parameter for predicting the machinery health condition. The t-Test conducted showed that mean differences in values of vibration signal data before and after failure are not zero but negatives (signal before failure < signal after failure). Outputs from tests of significance using two-tailed t-Test indicated that the differences in values of vibration data signals are not significant at ($p \leq 0.05$) when considering "equal variance not assumed". The non-significance of these mean differences may indicate that the present operational vibration signal level should be maintained at lower values in order that significant difference may be observed between periods before failure and after failure for efficient prediction of failure; as the present 1.5-3.5 mm/s range is likely not a good range for efficient failure prediction.

Keywords: CBM, cement plant, kiln induced draft fan, vibration, machinery health

1. Introduction

Cement manufacturing according to Cantini et al. [1], consists of three main categories of operations which include raw materials processing, clinker production and finish grinding processing. Cement is one of the most important materials that go into the production of concrete and sandcrete for building construction and other civil structural edifices [2]. There have been increases in the demand for cement over two decades [2-4] based on various structures that spring up in most especially growing economies which require construction of new road network systems and residential building to take care of increases in population. It has been said that cement production is one of the most energy consuming industries with 12-15% of the industry's total energy consumption being expended for this purpose while about 51% of it is lost in various forms [5-10]. Hence, it is imperative that the cement manufacturing processes

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are maintained without interruption by way of monitoring conditions of equipment which constitute the manufacturing plant, to ensure efficient and optimal utilization of the less than 50% available energy.

The philosophy of Condition-Based Maintenance (CBM) is a practical maintenance strategy which seeks to optimize the mix of failure-based, preventive, predictive, and proactive maintenance practices. The strategy is typically implemented by first identifying a Reliability Team that performs a qualitative assessment of plant processes and machinery to determine criticality of the assets in order to prevent disruption in production processes, which often runs into millions of Nigerian Naira. The rationale behind CBM practice involves timely restoration of faulty components by minimizing completion time and a way to achieve this is through close monitoring of components health condition in real-time, including operational changes which may pose possible failure [11] so that necessary actions could be taken when observed to have deviated from normal health status [12]. Appropriately collected operational data can be analyzed to acquire equipment conditions and afterwards, definite maintenance actions can be initiated timely [13]. Critical equipment according to Anders [14], include machines that are vital to a plant or process; they are a key part of a production process and are usually fully monitored to avoid failure. A good example such critical equipment is the kiln in cement making plant. Condition monitoring of plant equipment is key to effective and efficient production process to ensure optimal use of equipment, reduce breakdowns and long repair hours. However, the concept of condition-based monitoring is often overlooked or ignored including the consequences to overall effect on organization’s production goal. Failure occurs in some critical cement plant equipment mainly as a result of non-detection of the deteriorating condition or failure signs early enough during normal operation of the equipment. Failure can also be due to operational error and failure from upstream or downstream process stage.

Maintenance is implemented when there is existence of an objective and observable proof for potential occurrence of imminent failure [15]. To optimize production, ensure high equipment reliability and utilization, it is necessary to run the machines at high efficiency without premature and preventable failure or breakdown which disrupts production and leads to economic loss. This sort of increase in reliability and machine utilization was demonstrated in Adetunji et al. [16] as increase in cement production was recorded when computer maintenance management system became operational, leading to increase in revenue. Having made it known by Lv et al. [17] that “the Kiln Head Temperature (KHT) is a key thermal variable to condition monitoring and stable control of the rotary kiln”, they implemented a hybrid dynamic prediction framework to accurately predict the KHT chaotic time series in real-time and it was found that the implemented framework has the capability to capture dynamic evolution of KHT with respect to time. It has been shown in the work of Uit het Broek [18] that CBM policies are mainly effective in situation of required higher production with the risk of considerably higher failure rates. The authors also noted that the cost-effectiveness of CBM largely depends on maintenance planning time, corrective maintenance cost and the rate and volatility of deterioration process. The cost benefit of CBM becomes substantial for broad range of preventive maintenance cost but limited when preventive maintenance is extremely small or large [19]. Utilization of multi-feature techniques in a CBM as applied to monitoring high-speed centrifugal blowers in the work of Gowid et al. [20] indicated a promising reduction in fault interference potential. Deviation from the traditional measure of features such as vibration, temperature, pressure and acoustic emission, Famakinwa and Shibutani [21] attempted monitoring cylinder liner wear amount to aid decision making on maintenance policies formulation for marine engine cylinder liner via condition-based monitoring of Iron composition in drain cylinder oil sample. The authors implemented their condition-based monitoring using Gaussian Graphical Model which also extended to predict the remaining useful life of the cylinder liner. Manjunatha et al. [22] deployed a CBM system for monitoring health condition of nuclear power plant, exploring the advantage of machine learning, artificial intelligence, physics-informed modeling and visualization, realized significant improvement in fault prediction performances while reducing data heterogeneity. Rameshkumar et al. [23] also adopted the coast down time techniques as a potentially viable technique for condition health monitoring of rotating machine and its performance was proven. Based on available literature, it not evident that studies have been conducted to statistically evaluate vibration signal of KID before and after failure in order to present evidence of significance in vibration signal between period before failure and after failure for the purpose of ensuring efficient operation, considering set equipment operational vibration range. Therefore, this work evaluated the vibration signals of KID before failure and after failure by employing statistical analysis type of t-Test at 95% confidence, including determine the plane that is most appropriate for vibration health condition monitoring of the equipment.

2. Materials and Methodology

Materials and tools used in this work are Kiln induced draft fan (313FA17) of 400 kW rated power, CSI 2130 Machinery Health Analyzer Firmware, Machinery Health Manager Version 5.3, High Frequency accelerometer and Cable for use with accelerometer.

Kiln Induced Draft equipment was monitored for its operating condition using the above materials and tools to obtain parameter values for vibration as shown in Table 1. Data collection was conducted from October 2011 to December 2013 for the Kiln Induced Draft Fan before failure and February to December 2012 for periods after failure.

The vibration signals data from induced draft fan were captured using CSI 2130® Machinery health Analyzer as in Figure 1 via accelerometer probe (Figure 2) placed at the identified portion on the running equipment.

Table 1 - Equipment, data collected and planes of measurement

s/n	Measurement Plane	Data Captured	Equipment Type	Process Section
1.	Horizontal (motor and fan bearing ends, non-drive and drive)	Vibration (mm/s)	Kiln Induced Fan (313A17)	Burning
2.	Vertical (motor and fan bearing ends, non-drive and drive)			
3.	Axial (motor and fan bearing ends, non-drive and drive)			

An accelerometer makes use of piezoelectric (that is, pressure-sensitive) films to convert mechanical energy into electrical signals. Vibration signal data obtained were for three planes namely Vertical (V), Horizontal (H) and Axial (A) at the motor bearing and fan bearing ends respectively, before and after failure of the equipment. Machinery faults are clearly visible in the waveform at peak value, opening up new options for fault detection and diagnosis. Data obtained from measured vibration signals were subsequently subjected to t-Test statistics at 95% confidence to determine degree of significance between periods before failure and after failure.

Fig. 1 - CSI 2130 Machinery Health Analyzer

Fig. 2 - Accelerometer probe with magnetic base for onsite data capture

3. Results and Discussion

3.1 Vibration Data on Kiln Induced Draft Fan (313FA17)

The vibration data monitored over the period between October, 2011 and December, 2013 for the Kiln Induced Draft Fan (313FA17) at motor bearing, non-drive and drive ends (M1 and M2) and fan bearing, non-drive and drive ends (F1 and F2) respective, before failure are as presented in the Tables 2 and 3 while that obtained after failure for period between February and December 2012 are contained in Tables 4 and 5. The data presented in these tables shows relationship between vibration data for planes H, V and A for the motor bearing and fan bearing ends. It was observed that vibration measured along plane H for both motor bearing (non-drive and drive ends) and fan bearing (non-drive and drive ends) recorded higher values than data obtained along planes V and A, this is in agreement with values obtained in the work of Dutta et al. [24]. The same can be said of vibration signals obtained after failure and these values obtained for plane H increased by more than 120% on average when compared to that measured for period before failure, while for planes V and A, the vibration signal values obtained are far less than 100% increase on average (Figure 3). This may indicate that vibration signals measured in the H plane presents true health state of the equipment than the other planes and it is more appropriate to adopt as a measure of equipment health status. Making reference to the ISO 10816 standard chart [25] for a 400 kW Kiln Induced Draft Fan (313FA17), the mean plane H vibration signals obtained before failure are within satisfactory range while that obtained after failure crossed the satisfactory range into unsatisfactory region as expected. Increased vibration signal obtained after failure resulted from unbalance introduced as a result of failed units in the rotating equipment, leading to excessive vibration [26]. Other abnormal conditions which may be termed vibration precursors as indication of failed units are misalignment, looseness and resonance condition [27].

Table 2 - Vibration data for Kiln Induced Fan (313FA17) at motor bearing ends

Date	M1H (mm/s)	M1V (mm/s)	M1A (mm/s)	M2H (mm/s)	M2V (mm/s)	M2A (mm/s)
Oct., 2011	3.322	0.353	0.591	2.652	0.796	0.582
Nov., 2011	2.168	0.587	2.157	2.655	0.444	2.690
Jan., 2012	2.530	0.447	0.455	1.750	0.900	0.836
Feb., 2012	3.213	0.570	0.714	2.148	0.664	0.882
June, 2012	2.609	0.346	0.661	2.123	0.853	1.170
Oct., 2012	2.887	0.525	0.631	1.956	0.938	0.632
Feb., 2013	2.122	0.37	0.716	1.846	0.491	0.657
April, 2013	2.864	0.475	0.616	2.478	0.93	1.324
June, 2013	2.486	0.868	0.948	2.32	0.748	0.93
Nov., 2013	1.817	0.607	0.889	1.375	0.754	0.673
Dec., 2013	2.567	0.993	1.005	2.755	0.978	1.385

Table 3 - Vibration data for Kiln Induced Draft Fan (313FA17) at fan bearing ends

Date	F1H (mm/s)	F1V (mm/s)	F1A (mm/s)	F2H (mm/s)	F2V (mm/s)	F2A (mm/s)
Oct., 2011	2.789	0.482	1.506	2.042	0.5	1.754
Nov., 2011	2.343	0.493	2.628	2.172	0.572	2.095
Jan., 2012	2.159	0.454	2.512	1.744	0.496	1.211
Feb., 2012	2.122	0.474	4.275	1.698	0.624	2.095
June, 2012	1.073	0.527	4.340	1.104	0.466	3.922
Oct., 2012	1.791	0.453	4.648	1.067	0.656	3.151
Feb., 2013	3.169	0.498	3.591	2.937	0.738	2.382
April, 2013	2.228	0.426	2.059	2.744	0.598	1.246
June, 2013	2.353	0.712	3.287	1.847	0.771	1.157
Nov., 2013	2.454	0.484	3.513	1.735	0.528	2.187
Dec., 2013	3.813	0.81	3.781	3.24	0.779	2.072

Table 4 - Vibration data for Kiln Induced Draft Fan (313FA17) at motor bearing ends

Date	M1H (mm/s)	M1V (mm/s)	M1A (mm/s)	M2H (mm/s)	M2V (mm/s)	M2A (mm/s)
Feb. 2012	7.197	0.429	0.715	5.759	0.511	0.906
April, 2012	10.310	0.592	1.085	8.600	0.739	1.015
Aug. 2012	3.680	0.691	1.236	2.624	1.137	0.884
Oct. 2012	2.887	0.525	0.631	1.956	0.938	0.632
Dec. 2012	10.000	1.331	2.345	9.286	1.583	1.910

Table 5 - Vibration data for Kiln Induced Draft Fan (313FA17) at fan bearing ends

Date	F1H (mm/s)	F1V (mm/s)	F1A (mm/s)	F2H (mm/s)	F2V (mm/s)	F2A (mm/s)
Feb 2012	4.426	0.694	3.143	3.892	0.851	2.051
April, 2012	6.140	0.894	4.636	5.666	1.164	2.610
Aug. 2012	2.509	0.475	4.040	2.266	0.638	3.271
Oct. 2012	1.791	0.453	4.648	1.067	0.656	3.151
Dec. 2012	12.370	2.728	6.120	20.380	2.672	5.161

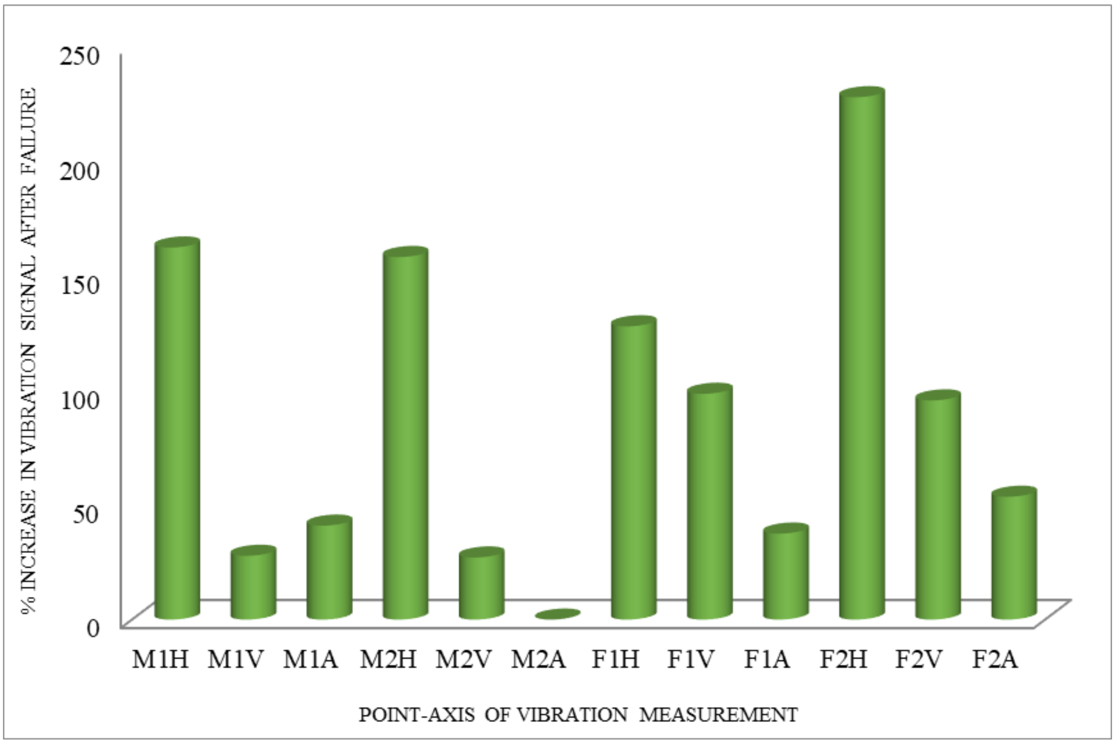
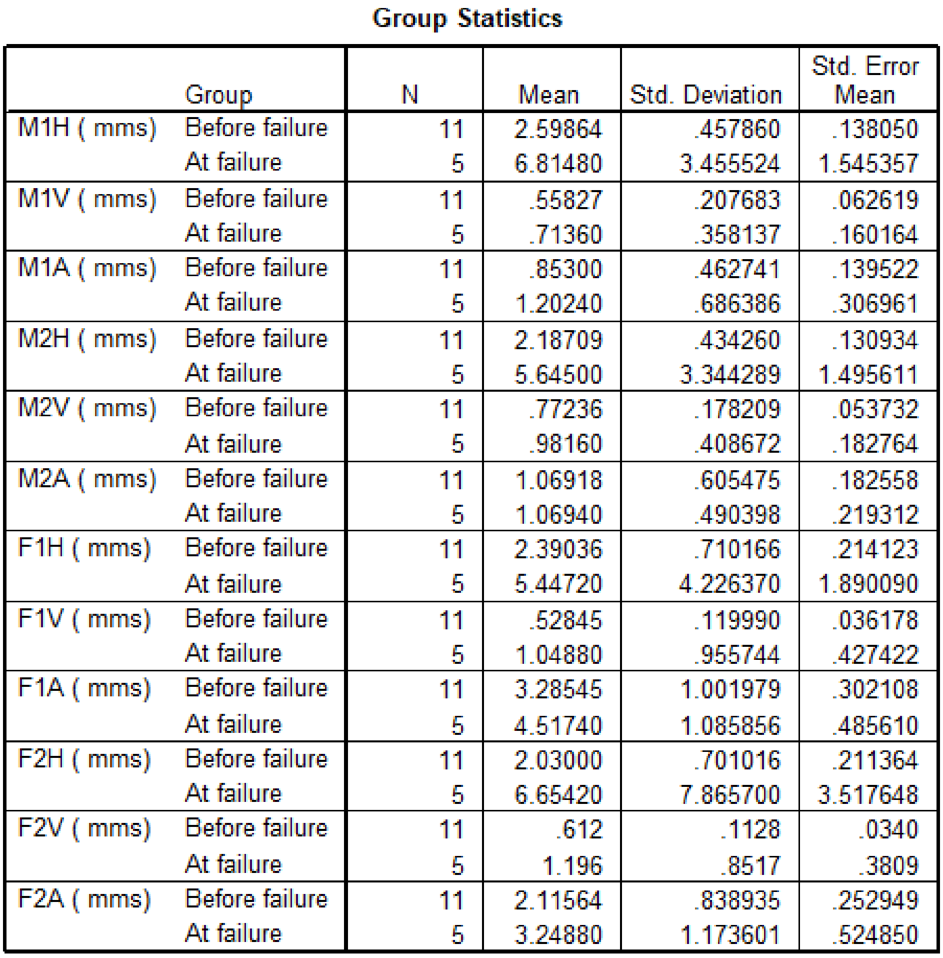


Fig. 3 - Percentage mean increase in vibration signal data after failure

3.2 Statistical Analysis of Vibration Data Collected

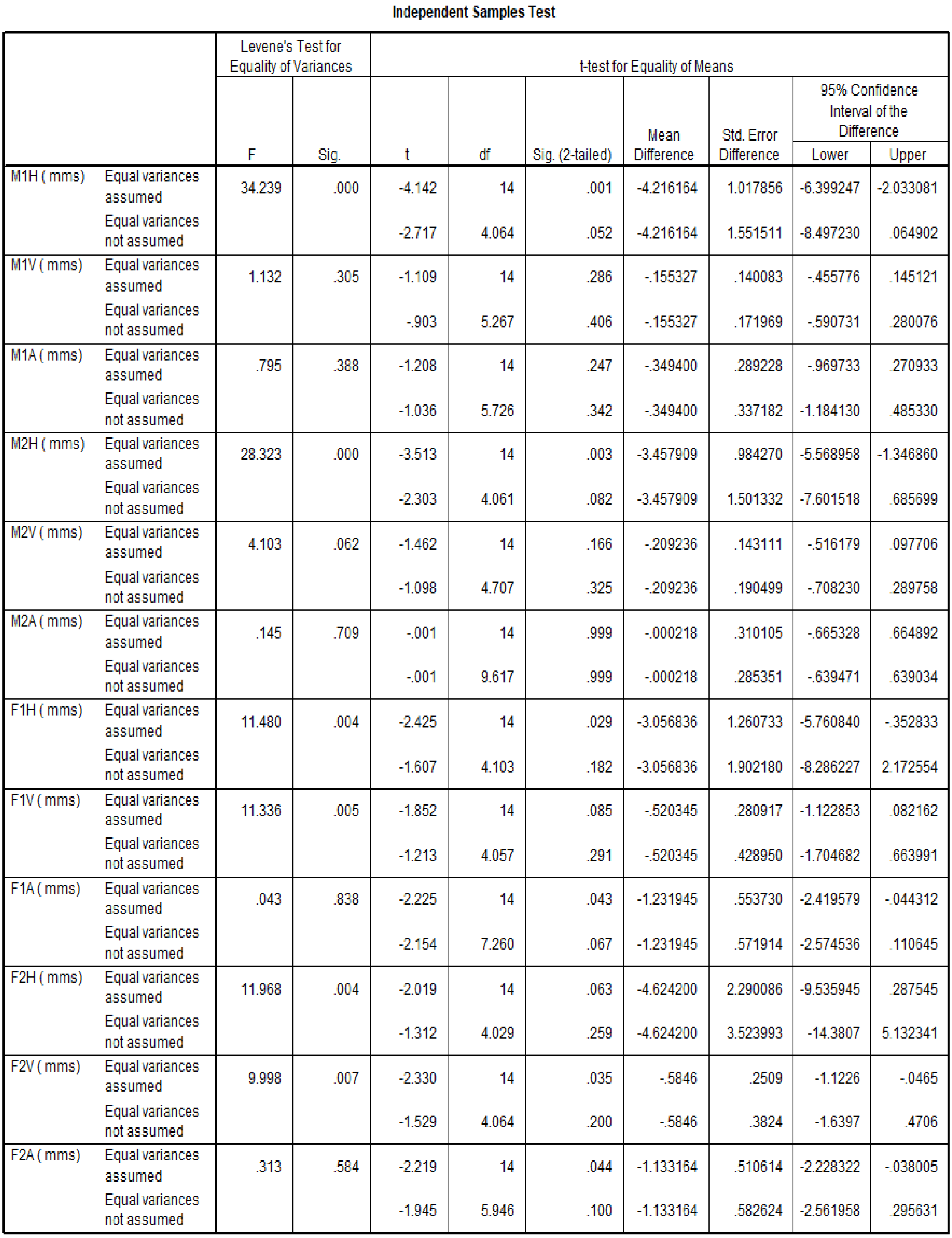
Data generated from measurement of vibration data for kiln induced draft fan on motor drive end (drive and non-drive) and fan drive end (drive and non-drive) in planes H, V and A subjected to statistical t-Test are as presented in Figures 4 and 5. Figure 4 shows mean and standard deviation of data collected for conditions before failure and after failure and Figure 5 presents test of significance in values of mean difference at 95% confidence. The mean vibration signals obtained before failure for M1H and F1H are higher than that obtained for M2H and F2H respectively, this is the case for signals obtained after failure and according to Orhon and Belek [28], these indicated transmission of vibrations to non-drive side via motor bearing and fan bearing structures respectively. Negative values of mean differences obtained imply that mean vibration data values before failure are lower than that obtained after failure. If equal variance is assumed, the p-value ($p \leq 0.05$) obtained for M1H, M2H, F1H, F2H, F1V and F2V showed that true differences between means for period before failure and after failure are not equal to zero and that these differences in vibration signals recorded are significant for one-tailed t-Test results. Same can be said for two-tailed t-Test results for M1H, M2H, F1H, F1A, F2V and F2A. But in this case, unequal variance can only be assumed as the sample sizes are unequal, and the standard deviations obtained cannot be assumed to be roughly equal. The p-values obtained under “equal variance not assumed” is ($p>0.5$) for two-tailed t-Test in all conditions of the kiln induced draft fan. Hence, the mean differences in vibration data before failure and after failure are not equal to zero but these mean differences are not statistically significant. In order for the mean difference in vibration signal to be significant, vibration before failure should be maintained well below current mean vibration levels for plane H. This is because the mean vibration data obtained may be an indication that the current operational vibration level of the equipment, though within the satisfactory range, is near failure and, must be maintained below “satisfactory” range and below currently adopted 1.5-3.5 mm/s range values by ensuring it is within “good” range in order to have a statistically significant effect of vibration signal after failure.



Group Statistics

	Group	N	Mean	Std. Deviation	Std. Error Mean
M1H (mms)	Before failure	11	2.59864	.457860	.138050
	At failure	5	6.81480	3.455524	1.545357
M1V (mms)	Before failure	11	.55827	.207683	.062619
	At failure	5	.71360	.358137	.160164
M1A (mms)	Before failure	11	.85300	.462741	.139522
	At failure	5	1.20240	.686386	.306961
M2H (mms)	Before failure	11	2.18709	.434260	.130934
	At failure	5	5.64500	3.344289	1.495611
M2V (mms)	Before failure	11	.77236	.178209	.053732
	At failure	5	.98160	.408672	.182764
M2A (mms)	Before failure	11	1.06918	.605475	.182558
	At failure	5	1.06940	.490398	.219312
F1H (mms)	Before failure	11	2.39036	.710166	.214123
	At failure	5	5.44720	4.226370	1.890090
F1V (mms)	Before failure	11	.52845	.119990	.036178
	At failure	5	1.04880	.955744	.427422
F1A (mms)	Before failure	11	3.28545	1.001979	.302108
	At failure	5	4.51740	1.085856	.485610
F2H (mms)	Before failure	11	2.03000	.701016	.211364
	At failure	5	6.65420	7.865700	3.517648
F2V (mms)	Before failure	11	.612	.1128	.0340
	At failure	5	1.196	.8517	.3809
F2A (mms)	Before failure	11	2.11564	.838935	.252949
	At failure	5	3.24880	1.173601	.524850

Fig. 4 - Estimation of mean and standard deviation of vibration signal for kiln induced draft fan



Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
M1H (mms)	Equal variances assumed	34.239	.000	-4.142	14	.001	-4.216164	1.017856	-6.399247	-2.033081
	Equal variances not assumed			-2.717	4.064	.052	-4.216164	1.551511	-8.497230	.064902
M1V (mms)	Equal variances assumed	1.132	.305	-1.109	14	.286	-.155327	.140083	-.455776	.145121
	Equal variances not assumed			-.903	5.267	.406	-.155327	.171969	-.590731	.280076
M1A (mms)	Equal variances assumed	.795	.388	-1.208	14	.247	-.349400	.289228	-.969733	.270933
	Equal variances not assumed			-1.036	5.726	.342	-.349400	.337182	-1.184130	.485330
M2H (mms)	Equal variances assumed	28.323	.000	-3.513	14	.003	-3.457909	.984270	-5.568958	-1.346860
	Equal variances not assumed			-2.303	4.061	.082	-3.457909	1.501332	-7.601518	.685699
M2V (mms)	Equal variances assumed	4.103	.062	-1.462	14	.166	-.209236	.143111	-.516179	.097706
	Equal variances not assumed			-1.098	4.707	.325	-.209236	.190499	-.708230	.289758
M2A (mms)	Equal variances assumed	.145	.709	-.001	14	.999	-.000218	.310105	-.665328	.664892
	Equal variances not assumed			-.001	9.617	.999	-.000218	.285351	-.639471	.639034
F1H (mms)	Equal variances assumed	11.480	.004	-2.425	14	.029	-3.056836	1.260733	-5.760840	-.352833
	Equal variances not assumed			-1.607	4.103	.182	-3.056836	1.902180	-8.286227	2.172554
F1V (mms)	Equal variances assumed	11.336	.005	-1.852	14	.085	-.520345	.280917	-1.122853	.082162
	Equal variances not assumed			-1.213	4.057	.291	-.520345	.428950	-1.704682	.663991
F1A (mms)	Equal variances assumed	.043	.838	-2.225	14	.043	-1.231945	.553730	-2.419579	-.044312
	Equal variances not assumed			-2.154	7.260	.067	-1.231945	.571914	-2.574536	.110645
F2H (mms)	Equal variances assumed	11.968	.004	-2.019	14	.063	-4.624200	2.290086	-9.535945	.287545
	Equal variances not assumed			-1.312	4.029	.259	-4.624200	3.523993	-14.3807	5.132341
F2V (mms)	Equal variances assumed	9.998	.007	-2.330	14	.035	-.5846	.2509	-1.1226	-.0465
	Equal variances not assumed			-1.529	4.064	.200	-.5846	.3824	-1.6397	.4706
F2A (mms)	Equal variances assumed	.313	.584	-2.219	14	.044	-1.133164	.510614	-2.228322	-.038005
	Equal variances not assumed			-1.945	5.946	.100	-1.133164	.582624	-2.561958	.295631

Fig. 5 - Test of significance in mean difference in vibration signal data for periods before and after failure

4. Conclusions

This work has successfully presented an evaluation of vibration signals data obtained by accelerometer probe placement at specified locations on the equipment and data capture via a machinery health manager software suite. The evaluation involved implementation of t-Test statistics at 95% confidence on vibration signal data obtained and it was found that mean differences in vibration data for period before failure and after failure were not significantly different and as such, the presently set operational vibration signal range of 1.5-3.5 mm/s may be reviewed by lowering the range values. Furtherance to this, the following bullet points are conclusion from results analysis obtained:

- Horizontal plane vibration signal data values obtained are quite higher than that in vertical and axial planes for both motor and fan bearings (non-drive and drive ends).
- The horizontal plane vibration signal data is most suitable for monitoring the equipment health condition since it is more pronounced.
- Vibration signal data in horizontal plane increased by more than 120% after equipment failure while less than 100% was observed in vertical and axial planes.
- The mean differences in vibration data between period before failure and after failure obtained from t-Test statistics are not significant ($p>0.05$) for all planes when condition is “equal variances not assumed”.
- In order to obtain statistical significance, the presently operational vibration signal range values of 1.5-3.5 mm/s in horizontal plane should be lowered for more effective maintenance and operation system.

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