ESTIMATION OF FAN BEARING DEGRADATION USING ACOUSTIC EMISSION ANALYSIS AND MAHALANOBIS DISTANCE

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Abstract: In order to estimate health conditions of fan bearings and predict their remaining life before failure, relevant features associated with their degradation must be identified. There are few published papers that deal with the selection of relevant features from acoustic emission signals for health condition estimation and life prediction of bearings in cooling fans.

For this study, acoustic emission signals were measured periodically during stress tests of cooling fans, from which a total of fifteen different acoustic emission features were extracted. Correlation coefficients between the acoustic emission features and stress duration were calculated in order to identify features which were associated with bearing degradation. The distinguishing characteristics of acoustic emission features were also described. By using a health index based on a Mahalanobis distance integrating the acoustic emission features selected from the correlation analysis, the health conditions of fan bearings were estimated over the duration of the stress test. Failure analysis of as-received and failed fan bearings was conducted to identify physical defects on surfaces of bearing elements and relate the evolution of the physical defects to the generation of acoustic emission. The approach presented in this paper helps to identify acoustic emission features associated with the evolution of the physical condition of fan bearings.

Key words: Acoustic emission; Ball bearing; Condition monitoring; Correlation; Fan; Degradation; Mahalanobis distance

1 Introduction: The reliability of a fan intended for use in a product should be assessed before the fan is approved for that application. This will establish whether the fan can be expected to meet or exceed the specified requirements in the application conditions within a specified period of time. The reliability assessment of fans is commonly accomplished through accelerated life testing. One of the constraints faced in planning accelerated life testing is the need to avoid changing the failure mechanisms which occur under the application conditions. Stress levels in accelerated life tests cannot be elevated indiscriminately. Thus, for cooling fans, the test time required for accelerated life testing is frequently many months. For example, the test time needed to generate the failure of 18 out of 48 fans was reported as eleven and a half months in an elevated temperature condition [1].

Prognostics and health management (PHM) is an enabling discipline consisting of technologies and methods to assess the reliability of a product in its actual life cycle conditions in order to determine the advent of failure and mitigate system risk [2]. PHM can be used to estimate the remaining life of cooling fans during accelerated testing based on signals from sensors used to monitor the fans. During qualification tests, the degradation of a fan can be estimated and the life of the fan can be predicted before failure of the fan occurs. This has the potential to reduce product development time for equipment manufacturers.

This paper focuses on health monitoring of fan bearings based on acoustic emission (AE) signals. AE is defined as the generation of elastic waves released from localized sources within a material when the material undergoes deformation [3]. Examples of physical processes associated with AE generation are: contacts of asperities on the surface of bearing elements, plastic deformation (or fracture) of contaminant and/or wear particles, and contacts between asperities and particles. During the life of a bearing, lubricant that prevents the surfaces of bearing elements from contacting each other degrades and loses effectiveness. The degradation of bearing lubricant allows increased metal-to-metal contact between bearing elements, resulting in the deformation of bearing materials, which generates AE waves. Therefore, acoustic emission analysis is a suitable technique for the health monitoring of bearings.

Health monitoring of bearings using AE analysis requires feature extraction from raw AE waveforms. Feature extraction helps to increase signal-to-noise ratio and improve correlation with bearing degradation. Features including AE count and AE peak amplitude have been used by previous researchers to identify the effect of contaminants in bearing grease on the intensity of AE signals generated [4][5]. Another feature, AE absolute energy, has also been investigated with respect to its usefulness for the health monitoring of bearings undergoing fatigue failure [6]. These papers present the ability of AE features to detect bearing failures. However, most of the published papers in this field do not evaluate the sensitivity of AE features to early stages of bearing degradation.

This paper aims to identify relevant AE features for estimating the health condition of bearings. Section 2 presents definitions of correlation coefficient and Mahalanobis distance that are used for analyzing AE features collected from fan bearing tests. Section 3 describes the experimental setup for monitoring acoustic emission signals of fan bearings. Section 4 discusses AE feature selection using the correlation coefficient approach. Based on the selected features from the correlation analysis, the health of bearings during accelerated testing was examined using a health index called Mahalanobis distance. Finally, failure analysis results of failed bearings are presented.

2 Mathematical Method: Correlation analysis is used for quantifying the relationship between AE features and stress duration of fan bearings. The application of the correlation analysis on AE features is simple and computationally undemanding. Multiple AE features were integrated into a single variable using Mahalanobis distance. The integration of multiple AE features into a single variable is useful to understand the health conditions of fan bearings over time.

2.1 Correlation Coefficient: The correlation coefficient is a measure of how strongly two variables are related to each other. When there are *n* pairs of observations, (x_1, y_1), (x_2, y_2), …(x_n, y_n), it is natural to speak of x and y have a positive relationship if large *x*'s are paired with large *y*'s and small *x*'s with small *y*'s, and a negative relationship if large *x*'s are paired with small *y*'s and small *x*'s with large *y*'s. Mathematically, the correlation coefficient, *r*, for *n* pairs (x_1, y_1), (x_2, y_2), …(x_n, y_n) is defined as follows.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

There is no absolute criterion for determining the strength of the correlation. However, as a rule of thumb, the correlation is regarded as strong if $0.8 \leq |r| \leq 1.0$, weak if $0 \leq |r| \leq 0.5$, and otherwise moderate [7].

2.2 Mahalanobis Distance: The Mahalanobis distance (MD) is a distance measure that is useful for determining the similarity of a training dataset to a test dataset. The dataset is a matrix composed of multiple variables (e.g., AE features). The MD approach allows multiple AE features to be integrated into a single index which reflects the collective deviation of the combined AE features from the initial healthy state represented by the training dataset. MD [8] is defined as follows.

$$MD = \frac{1}{p} Z C^{-1} Z^T$$

where *Z* is the vector of a standardized value of AE feature values, *C* is the correlation matrix calculated from a training dataset, and *p* is the number of parameters in *Z*. Since MD is a distance measure, the range for MD values is from 0 to infinity. If a test dataset is exactly the same as the training dataset, the MD value is 1.

3 Experimental setup: The fans used for this study have two ball bearings to support the rotor shaft. In Figure 1, one of the two ball bearings is shown. During the stress test, two types of fan samples were used. One type of sample was a fan with bearings containing a nominal amount of grease and some residual oil from the bearing manufacturing process. Another type of sample was a fan with bearings containing only the residual oil and no added grease. The difference between the two types of the fan samples are whether the nominal amount of grease was added to bearings or not. Grease that consists of soap emulsified with oil offers lubrication of bearing components over time and is designed for stability over the rated operating temperature range of the fan. On the other hand, exposure of the thin coating of residual oil to thermal stresses will cause it to physically and/or chemically degrade quickly compared to grease, allowing metal-to-metal contact of bearing components. The improper lubrication due to the degradation of the residual oil leads to physical damage of the surfaces of bearing components when the fan operates.

In order to measure AE signals generated by the deformation of bearing components, an acoustic emission transducer with a resonance frequency of 300 kHz was used. In order to hold the AE transducer on the fan surface and provide a transmission path of the AE signals, petro wax was applied between the surface of the fan and the AE transducer. The AE transducer was mounted close to the fan bearings to reduce transmission losses of the AE signal. Figure 2 illustrates the cross sectional view 1-1' indicated in Figure 1. The acoustic emission signals generated from the two bearings are transmitted through the metal sleeve, plastic frame, and petro wax to the acoustic emission transducer.

Figure 3 shows a schematic of the AE measurement instrumentation. The AE instrumentation consisted of a test fixture, acoustic emission transducer, amplifier, data acquisition board, and signal processing software on a desktop computer. The test fixture which held the fan was designed to reduce mechanical noise from the environment. The test fixture was fabricated based on the ECMA 275 standard (2002): "Measurement of Structure Borne Vibration Induced by Small Air Moving Devices" [9]. The signal from the AE transducer is amplified by 100 times by the amplifier. A data acquisition board was used to apply a bandpass filter with a frequency range of 100 kHz to 400 kHz, and digitize the signal. The data acquisition sampling rate was 1M samples/sec.

The fan samples were characterized at a rotational speed of 4,000 rpm and room temperature for a period of 10 seconds. Twelve hit-driven (HD) and three time-driven (TD) features were extracted from AE time-series waveform signals in real-time using PAC AEwin software package. HD features focus on the characteristics of a single AE event. A single AE event is defined as a collection of multiple AE hits whose waveform signal exceeds a predetermined threshold. The hit definition time (HDT) that separates one AE event from another AE event is predefined by the user based on typical patterns of AE within the material under test. An HDT of 600 μsec is recommended for steel materials [10] and was used in this study. An HD feature is only recorded if the threshold is exceeded. The threshold is commonly expressed in the unit of dB with a reference of 1μVolt. In the test, 40 dB was used for the threshold. TD features focus on the characteristics of an AE waveform over the entire AE sampling duration (10 seconds in this study). TD features are detected regardless of the threshold level. The definitions of all the AE features are found in [10].

Signal characterization of all fan samples was conducted prior to stressing. Fans were stressed in an oven at 70°C at the rated fan speed of 4,800 rpm. After the stress test started, signal characterization was conducted after 8, 16, 24, 48, 72, and 240 hours stressing. When a screeching or ringing sound from the fan bearings could be heard, the fan was regarded as failed. Thus failure was established based on the detection of audible sound rather than a quantitatively measured parameter. After failure the fan was not stressed any further. When the stress test completed, failure analysis was conducted. Bearings of the fan samples were disassembled to separate the cage, inner and outer races, balls, and two seal plates. Those bearing elements were cleaned with isopropyl alcohol using an ultrasonic cleaner. The surfaces of bearing elements were investigated using an optical microscope.

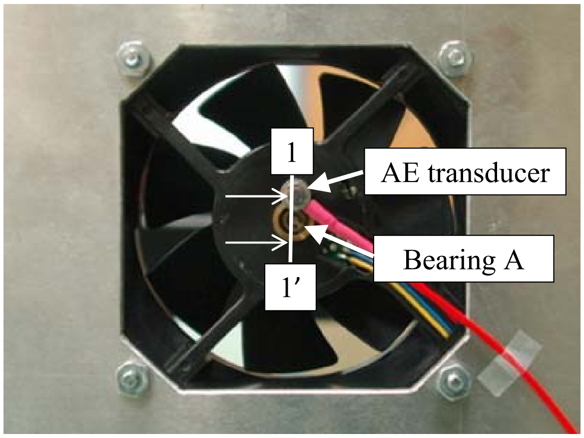

Figure 1: Fan Bearing with an AE transducer

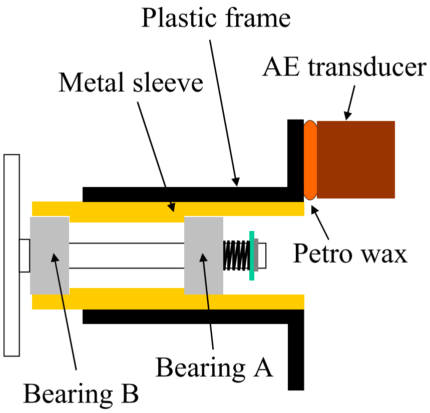

Figure 2: Illustration of Cross Sectional View 1-1'

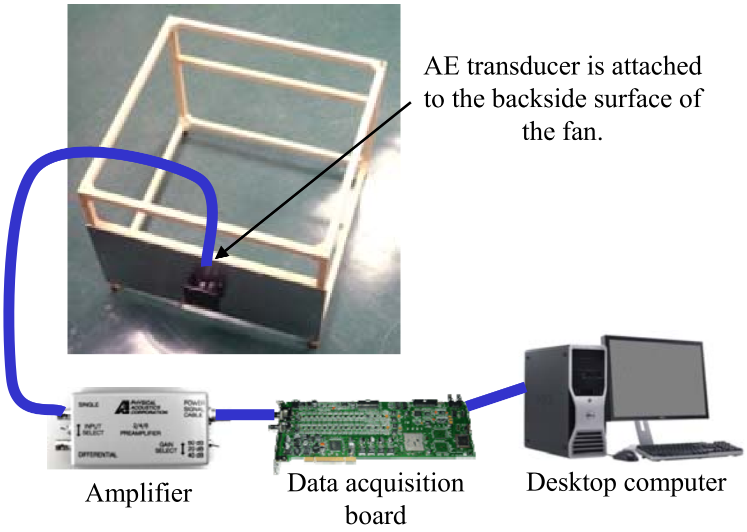

Figure 3: Schematic of AE Measurement Instrumentation

4 Results and Discussion: Audible sound was not observed over the stress duration of 240 hours from any of the three fans with bearings containing the nominal amount of grease. This result is reasonable since that period of time is too short to cause fan bearing failure. The life expectancy of the fan samples at their rated speed and maximum rated temperature was 5 years. In contrast, the fan with bearings containing only residual oil failed after the stress duration of 72 hours based on the observation of audible sound from the bearings. From the initial investigation of the fifteen AE feature values collected over the stress duration of 72 hours, trends were observed as the fans were stressed. In order to quantify the trends, correlation analysis between AE features and stress duration was conducted.

4.1 AE Feature Selection using Correlation Coefficient: One of the fifteen features, hit-driven rise time, is defined as the time between the first threshold-crossing and the peak of an AE hit [10]. Figure 4 shows the values of rise time plotted vs. stress duration. The correlation was 0.64. The rise time surged to 28.0 msec after 16 hours of stress. The rise time decreased to 22.5 msec at 48 hours and increased to 26.4 msec in the end. These uneven variations produced a correlation coefficient less than 1.0. Although the correlation between HD rise time and stress duration was moderate, the HD rise time could be a feature relevant to early detection of bearing degradation. Another example is illustrated in Figure 5. TD absolute power is the power of an AE signal over the time period between the start and the end of an AE measurement [10]. The correlation coefficient between absolute power and stress duration was 0.98. This larger number implies that the absolute power increased more linearly compared to the rise time, which would make it a better predictor of remaining life.

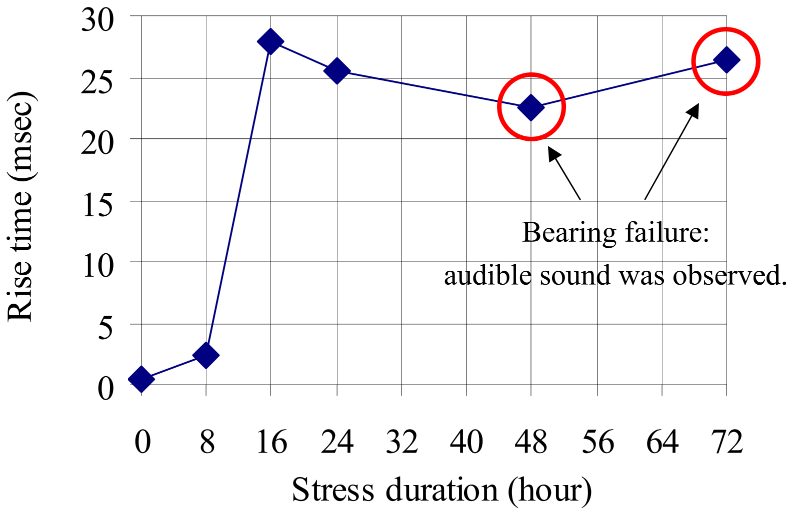

Figure 4: Moderate Correlation ($r = 0.64$) between Hit-driven Rise Time and Stress Duration

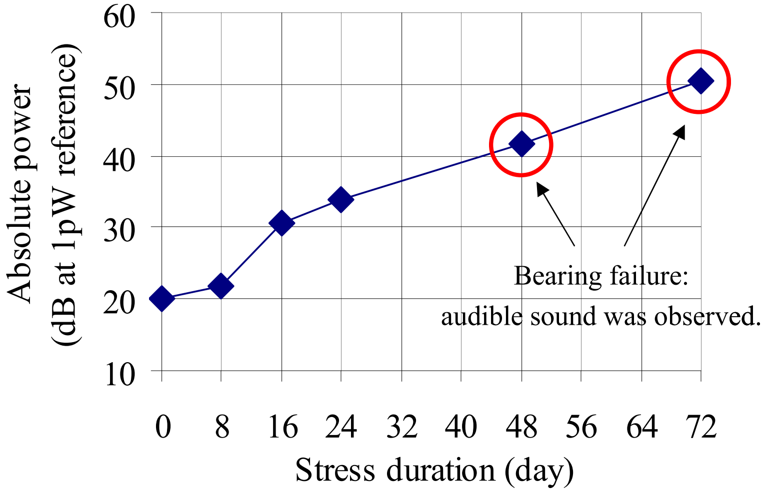

Figure 5: Strong Correlation ($r = 0.98$) between Time-driven Absolute Power and Stress Duration

Although there is not an absolute criterion for determining the strength of correlation between two variables, as a rule of thumb, the correlation is strong, moderate, and weak, if the absolute value of a correlation coefficient is 1.0 to 0.8, 0.8 to 0.5, and 0.5 to 0, respectively. A perfectly linear relationship between AE feature and stress duration does not necessarily imply a perfect degradation indicator. However, AE features may not be useful for estimating the degree of bearing degradation if the correlation is weak. In this study, the wear on the surface of the bearing elements is expected to become more severe as a fan runs longer under the stress condition. Thus one would expect strong correlation between acoustic emission and stress duration.

Table 1 shows the ranking of the twelve hit-driven features based on correlation coefficients. Eight HD features showed strong correlation. The correlation coefficient analysis helps to remove irrelevant features that do not show a trend during the degradation process. A strong correlation implies that, at minimum, 64% (square of the 0.8) of the observed variation of an AE feature over stress duration would be explained by the correlation. In contrast, a weak correlation implies that, at maximum, 25% (square of the 0.5) of the observed variation would be explained by the correlation. We focused on the eight HD AE features with strong correlation.

Another issue for feature selection is avoiding redundant features. For example, two HD features, HD root mean square and HD average signal level, are measures of the amplitude of the AE waveform. Although both features have strong correlation to stress duration, the inclusion of both HD features may produce redundancy. The selection of redundant features should be avoided, since they do not provide any additional information. Therefore, five HD features, including root mean square, average frequency over AE hits, absolute energy, peak amplitude, and hit count were selected.

Table 1: Correlation between Hit-driven AE Features and Stress Duration, Showing Selected Features in Shaded Boxes

Rank	Absolute value of correlation coefficient	Name of HD AE feature	Characteristic of AE feature
1	0.979	Root mean square	Amplitude
2	0.978	Average signal level	Amplitude
3	0.935	Average frequency over AE hits	Frequency
4	0.931	Absolute energy	Energy
5	0.917	Peak amplitude	Amplitude
6	0.873	Hit count	Count
7	0.843	Signal strength	Energy
8	0.840	PAC energy	Energy
9	0.745	Frequency centroid	Frequency
10	0.651	Hit duration	Time
11	0.637	Rise time	Time
12	0.586	Peak frequency	Frequency

Table 2: Correlation between Time-driven AE Features and Stress Duration, Showing Selected Features in Shaded Boxes

Rank	Absolute value of correlation coefficient	Name of TD AE feature	Characteristic of AE feature
1	0.980	Absolute power	Energy
2	0.980	Root mean square	Amplitude
3	0.979	Average signal level	Amplitude

Table 2 shows the ranking of three TD features. In the same way as the HD features were selected, we selected two TD features, TD absolute power and root mean square. The seven selected AE features were used for the estimation of the health of the fan bearings.

4.2 AE Health Index of a Fan using Mahalanobis Distance: Each row vector of a training dataset has seven elements that correspond to the seven AE features selected in Section 4.1. Each row vector contains AE feature values of the three fans with bearings containing grease from 0 to 240 hours stress duration. The training dataset was used to calculate the correlation matrix in the MD equation. The correlation matrix captures the relationship between AE features from the training dataset. Since MD is a distance measure, the range for MD values is from 0 to infinity. If a test dataset is the same as the training dataset, the MD value is 1. MD values calculated using the correlation matrix and the training dataset are shown in Figure 6. During the training period of 0 to 240 hours, the MD values ranged between 0.1 and 2.7.

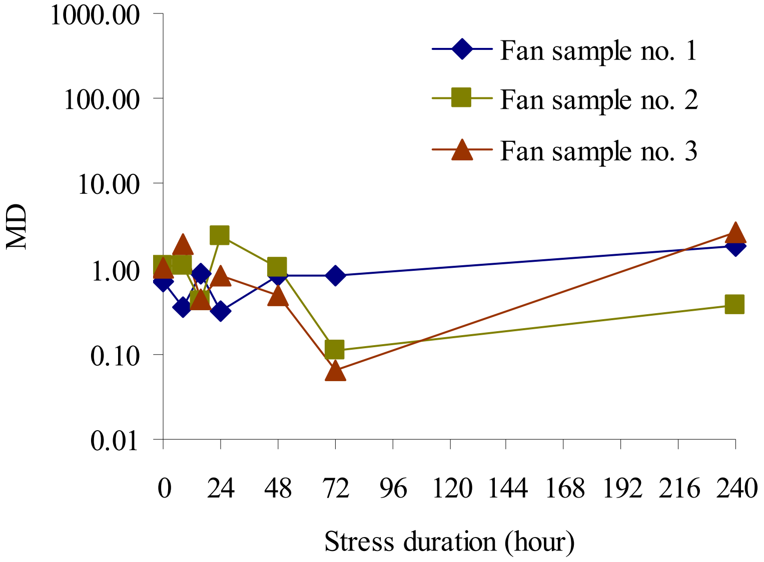

Figure 6: MD Trend of a Fan with Bearings Containing Grease

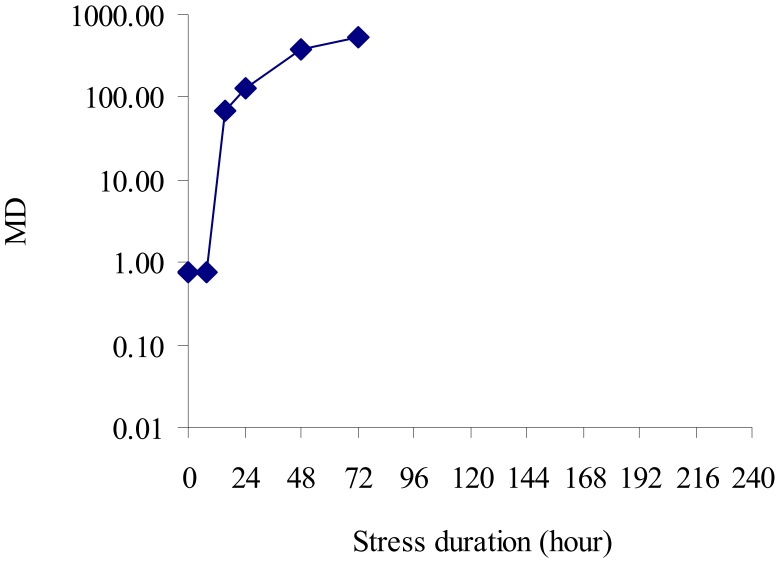

Figure 7: MD Trend of a Fan with Bearings Containing No Added Grease

When we calculate MD values using a test dataset from a fan with bearings containing no added grease and the correlation matrix from the training dataset, an increasing trend could be observed as shown in Figure 7. At 8 hours stressing, the MD value remained around 1. At the stress duration of 16 and 24 hours, the MD value increased to 68 and 128, respectively. After the stress duration of 48 hours with an MD value of 379, audible sound was observed from the fan bearing that indicated a failure. In the end, the MD value reached 524.

The health monitoring of fan bearings using acoustic emission signals indicated early detection of fan bearing failure. A surge of the MD values of the fan with bearings containing no added grease was observed from 8 to 16 hours of the stress duration, which resulted from a sudden increase of acoustic emission within the frequency range of 100 kHz to 400 kHz. However, the observation of sound audible to human ears was only after 48 hours stressing.

4.3 Failure Analysis: The surfaces of bearing elements, including inner and outer races and balls, from failed and unused fans were investigated. A difference between as-received and stressed bearings was the existence of surface defects. Surface defects were observed on all three bearing elements from the failed ungreased fan. In Figure 8, surface defects in the form of a dark track are shown. The track is shifted from the center line, since there was a spring in the fan assembly that pressed the inner race along the rotating axis. In Figure 9, the surface of the inner race of a greased bearing before stressing shows no evidence of defects.

Figure 8: Inner Race of Bearing from Failed Ungreased Fan Sample

Figure 9: Inner Race of Unused Bearing

5 Conclusions: The degradation of ball bearings in cooling fans was experimentally investigated. Correlation between acoustic emission (AE) features and stress duration was evaluated. Health conditions of fan bearings were estimated during degradation by using Mahalanobis distance (MD) analysis. Failure analysis of the failed fan bearings was conducted to identify physical defects on the surfaces of the bearing elements.

The correlation analysis between AE features and stress duration helped to select AE features that exhibit a trend during bearing degradation. Seven AE features out of a total of fifteen were selected from the correlation analysis. These seven features consisted of HD root mean square, HD average frequency over AE hits, HD absolute energy, HD peak amplitude, HD hit count, TD absolute power, and TD root mean square. The calculation of correlation coefficients is simple compared to mathematical methods such as principal component analysis. Correlation analysis is a quick and easy tool for understanding the relationship between AE features and bearing degradation.

The seven AE features selected from the correlation analysis were integrated into a single index from MD analysis. The MD index calculated from the AE signals provided early detection of fan bearing degradation compared to observations from audible sound. Although audible sound from degraded bearings was heard after the stress duration of 48 hours, the MD index indicated a change in the health of the bearings of an ungreased fan after 16 hours of stressing. The detection of bearing degradation using the MD approach based on AE signals occurred in one third the time required for observations audible to human ears.

Despite the use of accelerated test conditions, the time currently required for qualification testing of cooling fans is substantial compared to the product development time available for many electronic products. Although the stress tests in the present study used ball bearings containing no added grease, the approach in this paper could be extended to estimate health conditions of other fan bearings with nominal amounts of grease. The application of MD analysis to selected acoustic emission features to estimate the degradation of fan bearings can be useful for reducing the qualification time of cooling fans.

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