Implementing wavelet packet transform for valve failure detection using vibration and acoustic emission signals

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Abstract. The efficiency of reciprocating compressors relies heavily on the health condition of its moving components, most importantly its valves. Previous studies showed good correlation between the dynamic response and the physical condition of the valves. These can be achieved by employing vibration technique which is capable of monitoring the response of the valve, and acoustic emission technique which is capable of detecting the valves’ material deformation. However, the relationship/comparison between the two techniques is rarely investigated. In this paper, the two techniques were examined using time-frequency analysis. Wavelet packet transform (WPT) was chosen as the multi-resolution analysis technique over continuous wavelet transform (CWT), and discrete wavelet transform (DWT). This is because WPT could overcome the high computational time and high redundancy problem in CWT and could provide detailed analysis of the high frequency components compared to DWT. The features of both signals can be extracted by evaluating the normalised WPT coefficients for different time window under different valve conditions. By comparing the normalised coefficients over a certain time frame and frequency range, the feature vectors revealing the condition of valves can be constructed. One way analysis of variance was employed on these feature vectors to test the significance of data under different valve conditions. It is believed that AE signals can give a better representation of the valve condition as it can detect both the fluid motion and material deformation of valves as compared to the vibration signals.

1. Introduction
Reciprocating compressors are used extensively in the petrochemical industry due to its high compression ratio allowing large capacity of media to be transported over longer distance. Due to this high compression ratio, the valves of these compressors are more susceptible to wear and tear compared to other components. The failure of valves will lead to the pumping inefficiency and might cause secondary damage to other components of the compressor if the problem persists.

There are several techniques used in detecting valve problems, namely vibration, acoustic emission (AE) [1], crankshaft instantaneous angular speed [2], pressure, and temperature measurement. Non-destructive and non-intrusive diagnostic methods such as vibration and AE are always preferred as

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they are easier to install and give minimum interference to the operating condition of the compressor. Although comparison between vibration and AE signals in detecting valve failures was conducted in the previous study [3-4], detailed comparison between the two techniques was not performed besides visual inspection of both signals under different working conditions.

Due to the difference in operating frequency range between vibration and AE transducer, each of the transducer has its own capability in detecting different valve failure condition. To extract the signals in the time-frequency domain, wavelet analysis is preferable over Fourier transform (FT) and short time Fourier transform (STFT) due to its flexibility besides producing good resolution in both the time and frequency domain [5]. In fact, wavelet transform is excellent in extracting fault features in a signal, performing time-frequency analysis, detecting singularity, and de-noising weak signals [6]. It is employed in gear failure detection [7], structural damage identification [8], and engine fault diagnosis [9]. In this study, wavelet packet transform (WPT) is chosen as the signal processing technique to overcome the limitations of discrete wavelet transform (DWT) in which suffering from poor frequency resolution in the high frequency range [10]. In fact, wavelet packet transform (WPT) filters the signals into a smaller frequency range for better signal-to-noise ratio.

2. Theoretical Background

2.1. Wavelet packet transform

Wavelet packet transform (WPT) is a multi-resolution analysis technique employed to decompose the signals into different frequency segments. It is performed by passing the time signals into a high pass and low pass filters. Signals passing through the filters will be decimated by 2, causing a sample size reduction by 2 at every level of decomposition. This filtering process is repeated until the desired frequency range is obtained.

A wavelet packet function can be represented by three indices, \( n, j, \) and \( k \), where \( n \) denotes the modulation parameter, \( j \) denotes the scale parameter, and \( k \) denotes the translation parameter [9-10]. Equation 2.1 shows a typical wavelet packet function.

\[
W_{n,j,k}(t) = 2^{j/2}W^n_{2^j} (2^{j/2}t - k)
\]  

(2.1)

The decomposition is initiated by the scaling function, \( \phi(t) \) and the mother wavelet function, \( \psi(t) \) as displayed in Equation 2.2 and 2.3.

\[
W^0_{0,0}(t) = \phi(t)
\]  

(2.2)

\[
W^1_{0,0}(t) = \psi(t)
\]  

(2.3)

For further decomposition, when \( n = 2, 3..., \) recursive relationships in Equation 2.4 and 2.5 are applied.

\[
W^2_{0,0}(t) = \sqrt{2} \sum_k h(k)W^n_{1,k} (2^{j/2}t - k)
\]  

(2.4)

\[
W^{2^j+1}_{0,0}(t) = \sqrt{2} \sum_k g(k)W^n_{2^j,k} (2^{j/2}t - k)
\]  

(2.5)

where \( h(k) \) and \( g(k) \) are the quadrature mirror filter (QMF) associated with the predefined scaling function and mother wavelet function. Eventually, the wavelet packet coefficient \( w^n_{j,k} \) is computed as in Equation 2.6, with \( f(t) \) as the time signal.

\[
w^n_{j,k} = \left\langle f(t), W^n_{j,k} \right\rangle = \int f(t)W^n_{j,k}(t)dt
\]  

(2.6)

The wavelet packet coefficient is a measure of how closely related the time signal is to a frequency range, determined by scale factor \( j \). A high value of wavelet packet coefficients indicates that the signal is mostly composed of that particular frequency range.
The concept of WPT is shown in Figure 1. The original signal $S_0^0$ is decomposed into three resolution levels. $S_0^0$ represents the first subspace at third resolution level. In the present study, the AE and vibration signals are decomposed into three resolution levels, producing a total of 8 subspaces which correspond to a frequency range of 0-6.4 kHz, 6.4-12.8 kHz, 12.8-19.2 kHz, 19.2-25.6 kHz, 25.6-32.0 kHz, 32.0-38.4 kHz, 38.4-44.8 kHz, 44.8-51.2 kHz.

![Figure 1: WPT under three level decomposition [6]](image)

2.2. One way analysis of variance

The state of valves can be identified by comparing the value of wavelet packet coefficients under different valve failure conditions. Nevertheless, the reliability of this value often casts doubt as the difference of value between each condition might be resulted from the variability of data within each condition. One way analysis of variance was conducted in this study to compare the variation between each condition to the variation within them. It is a hypothesis test to determine whether the measured values fall in the same valve condition. A null hypothesis was made where there are no differences between each condition, and all conditions were normally distributed with the same mean and variance [11]. In other words, the mean of one condition was assumed to be equal to all other conditions. In this study, the hypothesis was tested at 0.05 significance level. If the probability computed is less than 0.05, the null hypothesis can be rejected and thus the values measured are from different condition.

To determine the probability of null hypothesis, the F-ratio, which is the ratio of between to within group (condition) variance is computed as $\sigma_c^2 / \sigma_w^2$. The variance of between group $\sigma_c^2$ and within group $\sigma_w^2$ is displayed in Equation 2.7 and 2.8, where $c$ denotes the total number of groups (conditions) to be compared, $n$ denotes the total number of samples within each group (conditions), $X_i$ denotes the mean in $i^{th}$ group (condition), $X_{ij}$ denotes the value of wavelet packet coefficients in $i^{th}$ group (condition) and $j^{th}$ samples, and $\bar{X}$ denotes the total mean value computed over all $i^{th}$ groups (conditions) and $j^{th}$ samples. The formulation of $\bar{X}$ is shown in Equation 2.9.

$$\sigma_c^2 = \frac{n}{c} \sum_{i=1}^{c} \left( \frac{X_i - \bar{X}}{c} \right)^2$$  \hspace{1cm} (2.7)
2.3. Tukey Comparison Test

If the one way analysis of variance leads to a conclusion that at least one group (condition) is different from others, the Tukey honest and significance difference (HSD) test can identify which pair of groups (conditions) are significantly different from each other. This statistical method is frequently used in examining the performance of different research methods [12]. The confidence interval, \( C \) for each pair of groups (conditions) is computed from the studentized range \((q)\) distribution and is shown in Equation 2.10. \( \bar{X}_i - \bar{X}_j \) denotes the mean difference between \( i^{th} \) group and \( j^{th} \) group, \( q_{\alpha,N-r} \) denotes the critical value of the studentized range at significant level \( \alpha \), \( r \) groups and \( N-r \) degree of freedom with \( N \) denotes total number of samples in all groups, and \( n \) denotes the number of samples in each group with the assumption that the sample size for each group is equal. The within group mean-square \( \hat{\sigma} \) can be computed from Equation 2.11.

\[
\sigma_n^2 = \frac{\sum_{i=1}^{c} \sum_{j=1}^{n} (X_{ij} - \bar{X})^2}{cn(n-1)}
\]  

\[ \bar{X} = \frac{\sum_{i=1}^{c} \sum_{j=1}^{n} X_{ij}}{cn} \]  

\[ C = \bar{X}_i - \bar{X}_j \pm \frac{q_{\alpha,N-r}}{\sqrt{2}} \frac{\hat{\sigma}}{n} \]  

\[ \hat{\sigma} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} (X_{ij} - \bar{X})^2}{n(n-1)} \]

From the F-ratio, the probability of null hypothesis can be obtained from the F-distribution. If the probability of null hypothesis computed is smaller than 0.05, it can be concluded that at least one group (condition) is different from the other groups (conditions).

3. Experimental procedure

The experimental setup for this study is illustrated in Figure 2, which consists of a single stage, 2 cylinders air cooled reciprocating compressors connected to a three-phase inverter to run at a speed of 450 rpm. A uniaxial Integrated Electronics Piezoelectric (IEPE) accelerometer with a frequency range of 1 to 6 kHz and an acoustic emission (AE) sensor with a frequency response of approximately 100 to 450 kHz were mounted on the suction valve cover to measure the vibration and AE signals, respectively. Both signals were acquired through a 4-channel data acquisition device (DAQ) with a sampling rate of 102.4 kHz. The signals were digitized and conditioned by the DAQ device before transmitted to a computer installed with LabVIEW for further analysis.

The acquisition of both vibration and AE signals started when the DAQ device received a reference signal from a laser tachometer. The tachometer will send a reference signal to the DAQ device whenever it received a pulse from the reflective tape attached to the flywheel of the compressor, as illustrated in Figure 2(b). Each pulse sent represented a piston position at the top-dead-centre (TDC), thus enabling the signals to be acquired at its corresponding piston position. A crank angle of \( 0^\circ \) corresponded to the piston position at the TDC while a crank angle of \( 180^\circ \) corresponded to the piston position at the bottom-dead-centre (BDC). The signals acquired will be averaged synchronously with respect to the crank angle over 50 averages before they were saved for post-analysis.
This study examined the vibration and AE signals when the valve plate was in the normal, grease, and leakage conditions. The grease condition was simulated by applying a layer of grease onto the valve plate to emulate the condition of valve stickiness due to excessive oil distribution while the leakage condition was simulated by grinding a small passage of 3mm width on the valve plate to emulate the condition of valve degradation. The physical condition of the valve plate is displayed in Figure 3.

A total of 40 vibration and 40 AE signal samples were acquired from each condition. These signals were further decomposed into 8 smaller frequency ranges by using wavelet packet transform (WPT) algorithm with a B-spline mother wavelet function and third level of resolution in MATLAB.

To correlate the signal with the major valve events in each frequency range, the signals after WPT were further segregated into 4 time segments, with the first, second, third, and fourth time segments corresponded to a crankshaft movement of approximately 0°-18.8°, 18.8°-131.4°, 131.4°-244°, and 244°-360° respectively. The valve failure can then be identified by comparing the normalised coefficients for each time segments under different valve conditions. Equation 3.1 expressed the normalised coefficients \( Z \), where \( w_i \) denotes the WPT coefficients, \( u \) and \( t \) denote the beginning and ending time of a particular time segment, and \( T \) denotes the period of the signal.
As there were 8 frequency ranges and 4 time segments in each frequency range, a total of 32 normalised coefficients revealing the physical condition of the valve were computed for each sample. To identify the time segment and frequency range which can distinguish different valve condition clearly from the value of normalised coefficients, one way analysis of variance was performed. If the probability of null hypothesis in a particular frequency range and time segment is smaller than 0.05, the null hypothesis can be rejected and thus at least one condition can be distinguished clearly from the other conditions. Consequently, a confidence interval can be computed through Tukey test for each pair of condition in this particular frequency range. If the confidence interval does not include a zero (non-overlapping confidence interval), it can be concluded that these conditions differ significantly with each other. Thus this particular time-frequency segment can identify different valve conditions effectively. The flow chart of this study is depicted in Figure 4.

\[ Z = \frac{\sum_{i} w_i^2}{\sum_{i} w_i^2} \]  

(3.1)
4. Results and Discussions

4.1. Comparison of vibration and AE signals before WPT

The vibration and AE signals acquired under normal, grease and leakage valve conditions are overlaid and depicted in Figure 5 and 6. Under the grease condition, the valve might not be fully closed, thus lesser pressure was required to open the valve. This can be shown in Figure 5, where there is a sudden rise at the crank angle approximately at 25° after TDC from the vibration signal. This gives an indication of early valve opening event as this rise occurs slightly later under the normal condition, at the crank angle of approximately 45°. Besides, a sudden peak can be observed at the crank angle of 190° from the vibration signal, which corresponds to the crankshaft movement from BDC to TDC. It can be deduced that the valve plate was not fully closed under the grease condition and thus fluttering occurs when the piston started to move up. However, both peaks are not obvious from the AE signal as the signal is contaminated with other noise. The early peak of AE signal at the crank angle of 0° to 20° might be attributed to the fluid flowing on the valve surface before the pressure was sufficient to push open the valve. This shows that AE can detect both the mechanical and fluid motion, as oppose to the vibration signal, where it can detect mostly mechanical motion of the valve.

Under the leakage condition, more noise can be observed at the crank angle approximately 240° to 360°, when the piston is moving from BDC to TDC, compressing the fluid out through discharge valve. Instead of flowing through the discharge valve, the leakage at the suction valve might cause part of the fluid to flow through, thus generating more noise compared to the normal condition.
The four major events of the valve operation, namely the fluid suction, valve opening, fluid compression, and fluid discharge mostly occurred at crank angle of $0^\circ$-$18.8^\circ$, $18.8^\circ$-$131.4^\circ$, $131.4^\circ$-$244^\circ$, and $244^\circ$-$360^\circ$, respectively. The vibration and AE signals were segregated by these four major events into four different time segments. 40 normalised coefficients of the four time segments for AE and vibration signals under different conditions are shown as a box plot in Figure 7 and 8. The red centre line represents the median of the samples while the edges of the box represent the first quarter and third quarter of the samples. Values beyond the length of the whiskers are defined as outliers and plotted as a cross mark in the box plot.
To examine the data reliability, a hypothesis test was conducted through one way analysis of variance. Since all the probability values are greater than 0.05, the null hypothesis can be rejected. Thus, it can be confirmed that at least one condition is different from other conditions at 95% confidence interval, as shown in Table 1.

| Signal type | Time 1         | Time 2         | Time 3         | Time 4         |
|-------------|----------------|----------------|----------------|----------------|
| AE          | 1.51E-37       | 4.09E-22       | 8.06E-33       | 6.43E-28       |
| Vibration   | 1.70E-27       | 3.43E-19       | 9.58E-08       | 4.30E-16       |

To compare the pairs of group significantly different from each other, the confidence interval of each group at each time segment was computed for vibration and AE signals. It can be shown from Table 2 that the normal condition (group 1) and leakage condition (group 3) at time segment 3 do not differ significantly with each other from the vibration signal, as a zero is included in the confidence interval (overlapping interval). On the other hand, for the AE signal, the normal condition (group 1) and leakage condition (group 3) at time segment 3 and 4 are not well separated. Therefore, it can be concluded that although grease condition can be identified clearly, other fault condition such as a small leakage is barely perceptible from the raw signal. This is shown clearly in the AE signal, where the mean difference between the normal and leakage condition is very small, thus increasing the difficulty in separating the later from the former at time segment 3 and 4. Thus, WPT is conducted in the next section to decompose the signal into a smaller frequency range, enabling the signals being analyzed to have a better signal-to-noise ratio, thus increasing the possibility of separating the normal and faulty signal.
### Table 2: Confidence interval (C.I) of raw signal from Tukey test

| Time Segments | Group Comparison | Vibration | AE |
|---------------|------------------|-----------|----|
|               |                  | C.I (lower) | Mean difference between group | C.I (higher) | Mean difference between group |
| T1            | 1 2              | -0.020     | -0.016 | -0.013 | -0.068 | -0.056 | -0.043 |
|               | 1 3              | 0.001      | 0.004  | 0.008  | 0.035  | 0.047  | 0.060 |
|               | 2 3              | 0.017      | 0.020  | 0.024  | 0.090  | 0.103  | 0.115 |
| T2            | 1 2              | 0.196      | 0.250  | 0.303  | -0.268 | -0.224 | -0.180 |
|               | 1 3              | 0.047      | 0.100  | 0.154  | -0.118 | -0.074 | -0.031 |
|               | 2 3              | -0.203     | -0.149 | -0.096 | 0.106  | 0.150  | 0.193 |
| T3            | 1 2              | -0.051     | -0.031 | -0.012 | -0.045 | -0.039 | -0.033 |
|               | 1 3              | -0.002     | 0.018  | 0.037  | -0.006 | 0.000  | 0.007 |
|               | 2 3              | 0.030      | 0.049  | 0.069  | 0.033  | 0.039  | 0.046 |
| T4            | 1 2              | -0.252     | -0.202 | -0.153 | 0.263  | 0.319  | 0.375 |
|               | 1 3              | -0.172     | -0.123 | -0.073 | -0.029 | 0.027  | 0.083 |
|               | 2 3              | 0.031      | 0.080  | 0.129  | -0.348 | -0.292 | -0.236 |

4.2. Comparison of vibration and AE signals after WPT

To improve the signal-to-noise ratio, the vibration and AE signals were decomposed into 8 smaller frequency ranges through WPT, where the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, and 8th frequency correspond to a frequency range of 0-6.4 kHz, 6.4-12.8 kHz, 12.8-19.2 kHz, 19.2-25.6 kHz, 25.6-32.0 kHz, 32.0-38.4 kHz, 38.4-44.8 kHz, and 44.8-51.2 kHz, respectively.

The ability of vibration and AE signals in detecting different valve conditions were examined by comparing the confidence intervals of both signals between different conditions at all time segments and frequency ranges, as displayed in Table 3. The pair of conditions having a zero in its confidence interval is shaded grey as they do not differ significantly with each other. For vibration signals, the normal, grease, and leakage conditions can be clearly separated at frequency 1 and time segment 1 and 4, frequency 2 and time segment 2 and 4, frequency 3 and time segment 2, frequency 4 and time segment 2 and 3, frequency 5 and time segment 2, frequency 6 and time segment 2 and 3, frequency 7 and time segment 1, 2, 3, and 4, frequency 8 and time segment 1, 2, 3, and 4. For AE signals, all conditions can be well separated at frequency 1 and time segment 1, frequency 2 and time segment 1, frequency 3 and time segment 1 and 4, frequency 4 and time segment 1, 2, and 4, frequency 5 and time segment 1, 2, and 4, frequency 6 and time segment 1, 2, 3, and 4, frequency 7 and time segment 1, and 4, frequency 8 and time segment 1, 2, and 4. All conditions cannot be separated at frequency 8 and time segment 3 for AE signal as its probability of null hypothesis is greater than 0.05, thus all groups cannot be distinguished from one another.
Table 3: Confidence interval (C.I) of WPT signal from Tukey Test

| Frequency | Time Segments | Group Comparison | Vibration | AE |
|-----------|---------------|------------------|-----------|----|
|           |               |                  | C.I (lower) | Mean difference between group | C.I (higher) | Mean difference between group |
|           | 1 (0-6.4 kHz) |                  |           |                              |              |                                  |
| T1        | 1 2           |                  | -0.030    | -0.022                        | -0.015       | -0.080                        | -0.067       | -0.055                        |
|           | 1 3           |                  | 0.011     | 0.018                         | 0.026        | 0.020                         | 0.033        | 0.045                        |
|           | 2 3           |                  | 0.033     | 0.041                         | 0.048        | 0.088                         | 0.100        | 0.113                        |
| T2        | 1 2           |                  | 0.278     | 0.340                         | 0.401        | -0.274                        | -0.230       | -0.187                        |
|           | 1 3           |                  | -0.009    | 0.053                         | 0.114        | -0.064                        | -0.020       | 0.023                        |
|           | 2 3           |                  | -0.349    | -0.287                        | -0.225       | 0.166                         | 0.210        | 0.254                        |
| T3        | 1 2           |                  | -0.051    | -0.031                        | -0.012       | -0.050                        | -0.043       | -0.036                        |
|           | 1 3           |                  | -0.012    | 0.007                         | 0.027        | -0.005                        | 0.002        | 0.009                        |
|           | 2 3           |                  | 0.019     | 0.038                         | 0.058        | 0.038                         | 0.045        | 0.052                        |
| T4        | 1 2           |                  | -0.351    | -0.286                        | -0.221       | 0.285                         | 0.341        | 0.397                        |
|           | 1 3           |                  | -0.143    | -0.078                        | -0.013       | -0.070                        | -0.014       | 0.042                        |
|           | 2 3           |                  | 0.143     | 0.208                         | 0.273        | -0.411                        | -0.355       | -0.299                        |
|           | 2 (6.4-12.8 kHz) |              |           |                                |              |                                  |              |                                  |
| T1        | 1 2           |                  | -0.012    | -0.010                        | -0.008       | -0.013                        | -0.009       | -0.006                        |
|           | 1 3           |                  | -0.001    | 0.001                         | 0.003        | 0.010                         | 0.014        | 0.017                        |
|           | 2 3           |                  | 0.008     | 0.010                         | 0.012        | 0.019                         | 0.023        | 0.027                        |
| T2        | 1 2           |                  | 0.146     | 0.196                         | 0.245        | 0.126                         | 0.182        | 0.238                        |
|           | 1 3           |                  | 0.040     | 0.090                         | 0.139        | -0.063                        | -0.007       | 0.049                        |
|           | 2 3           |                  | -0.155    | -0.106                        | -0.056       | -0.246                        | -0.190       | -0.134                        |
| T3        | 1 2           |                  | -0.039    | -0.020                        | 0.000        | -0.014                        | -0.002       | 0.009                        |
|           | 1 3           |                  | 0.008     | 0.028                         | 0.047        | 0.004                         | 0.016        | 0.027                        |
|           | 2 3           |                  | 0.028     | 0.047                         | 0.067        | 0.006                         | 0.018        | 0.030                        |
| T4        | 1 2           |                  | -0.209    | -0.166                        | -0.124       | -0.224                        | -0.171       | -0.118                        |
|           | 1 3           |                  | -0.160    | -0.118                        | -0.076       | -0.075                        | -0.022       | 0.031                        |
|           | 2 3           |                  | 0.006     | 0.048                         | 0.090        | 0.096                         | 0.149        | 0.202                        |
|           | 3 (12.8-19.2 kHz) |            |           |                                |              |                                  |              |                                  |
| T1        | 1 2           |                  | -0.008    | -0.006                        | -0.005       | -0.013                        | -0.011       | -0.008                        |
|           | 1 3           |                  | -0.001    | 0.000                         | 0.001        | 0.003                         | 0.005        | 0.007                        |
|           | 2 3           |                  | 0.005     | 0.006                         | 0.008        | 0.013                         | 0.016        | 0.018                        |
| T2        | 1 2           |                  | 0.090     | 0.131                         | 0.172        | 0.188                         | 0.236        | 0.284                        |
|           | 1 3           |                  | 0.021     | 0.062                         | 0.103        | -0.024                        | 0.024        | 0.072                        |
|           | 2 3           |                  | -0.110    | -0.069                        | -0.028       | -0.261                        | -0.212       | -0.164                        |
| T3        | 1 2           |                  | -0.022    | -0.004                        | 0.014        | 0.002                         | 0.016        | 0.030                        |
|           | 1 3           |                  | 0.009     | 0.027                         | 0.045        | 0.002                         | 0.016        | 0.031                        |
|           | 2 3           |                  | 0.013     | 0.031                         | 0.049        | -0.014                        | 0.000        | 0.015                        |
|           | 1 2           |                  | -0.154    | -0.121                        | -0.088       | -0.286                        | -0.241       | -0.197                        |
|           | 1 3           |                  | -0.122    | -0.089                        | -0.056       | -0.089                        | -0.045       | -0.004                        |
|   | T4 | 2   | 3   | 0.001 | 0.032 | 0.065 | 0.152 | 0.196 | 0.241 |
|---|----|-----|-----|-------|-------|-------|-------|-------|-------|
|   | T1 | 1   | 2   | -0.026 | -0.020 | -0.014 | -0.021 | -0.014 | -0.006 |
|   |    | 1   | 3   | -0.004 | 0.002 | 0.008 | 0.017 | 0.024 | 0.031 |
|   |    | 2   | 3   | 0.016 | 0.022 | 0.028 | 0.030 | 0.038 | 0.045 |
|   | T2 | 1   | 2   | 0.208 | 0.254 | 0.301 | 0.200 | 0.242 | 0.285 |
|   |    | 1   | 3   | 0.046 | 0.093 | 0.139 | 0.014 | 0.057 | 0.099 |
|   |    | 2   | 3   | -0.208 | -0.162 | -0.115 | -0.228 | -0.186 | -0.143 |
|   | T3 | 1   | 2   | 0.092 | -0.073 | -0.054 | -0.020 | -0.001 | 0.018 |
|   |    | 1   | 3   | 0.021 | 0.040 | 0.060 | 0.053 | 0.072 | 0.091 |
|   |    | 2   | 3   | 0.094 | 0.113 | 0.133 | 0.055 | 0.073 | 0.092 |
|   | T4 | 1   | 2   | -0.0196 | -0.161 | -0.126 | -0.277 | -0.228 | -0.178 |
|   |    | 1   | 3   | -0.170 | -0.135 | -0.099 | -0.202 | -0.153 | -0.103 |
|   |    | 2   | 3   | -0.009 | 0.026 | 0.062 | 0.026 | 0.075 | 0.124 |
|   | T1 | 1   | 2   | 0.225 | 0.263 | 0.301 | 0.234 | 0.275 | 0.315 |
|   |    | 1   | 3   | 0.094 | 0.133 | 0.171 | 0.025 | 0.066 | 0.106 |
|   |    | 2   | 3   | -0.169 | -0.130 | -0.092 | -0.250 | -0.209 | -0.168 |
|   | T2 | 1   | 2   | -0.116 | -0.098 | -0.080 | -0.034 | -0.011 | 0.013 |
|   |    | 1   | 3   | 0.017 | 0.002 | 0.020 | 0.054 | 0.077 | 0.100 |
|   |    | 2   | 3   | 0.081 | 0.100 | 0.118 | 0.064 | 0.087 | 0.111 |
|   | T3 | 1   | 2   | -0.170 | -0.142 | -0.114 | -0.293 | -0.243 | -0.193 |
|   |    | 1   | 3   | -0.159 | -0.131 | -0.103 | -0.210 | -0.161 | -0.111 |
|   |    | 2   | 3   | -0.017 | 0.011 | 0.039 | 0.033 | 0.082 | 0.132 |
|   | T4 | 1   | 2   | -0.017 | -0.014 | -0.010 | -0.034 | -0.028 | -0.022 |
|   |    | 1   | 3   | -0.003 | 0.001 | 0.004 | 0.013 | 0.019 | 0.026 |
|   |    | 2   | 3   | 0.011 | 0.014 | 0.018 | 0.041 | 0.048 | 0.054 |
|   | T1 | 1   | 2   | 0.152 | 0.196 | 0.240 | 0.274 | 0.312 | 0.350 |
|   |    | 1   | 3   | 0.070 | 0.114 | 0.158 | 0.006 | 0.044 | 0.082 |
|   |    | 2   | 3   | -0.126 | -0.082 | -0.038 | -0.306 | -0.268 | -0.230 |
|   | T2 | 1   | 2   | -0.131 | -0.110 | -0.089 | 0.007 | 0.029 | 0.052 |
|   |    | 1   | 3   | -0.050 | -0.029 | -0.009 | 0.038 | 0.060 | 0.083 |
|   |    | 2   | 3   | 0.059 | 0.080 | 0.101 | 0.009 | 0.031 | 0.053 |
|   | T3 | 1   | 2   | -0.102 | -0.073 | -0.043 | -0.360 | -0.313 | -0.267 |
|   |    | 1   | 3   | -0.115 | -0.085 | -0.055 | -0.170 | -0.124 | -0.077 |
|   |    | 2   | 3   | -0.043 | -0.013 | 0.017 | 0.143 | 0.189 | 0.236 |
|   | T4 | 1   | 2   | -0.012 | -0.008 | -0.005 | -0.038 | -0.031 | -0.025 |
|   |    | 1   | 3   | 0.005 | 0.009 | 0.013 | 0.006 | 0.013 | 0.019 |
|   |    | 2   | 3   | 0.013 | 0.017 | 0.021 | 0.038 | 0.044 | 0.051 |
|   | T1 | 1   | 2   | 0.233 | 0.273 | 0.313 | 0.359 | 0.403 | 0.447 |
|   |    | 1   | 3   | 0.101 | 0.141 | 0.181 | -0.017 | 0.027 | 0.071 |
### Table

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
| T2 | 1 | 2 | -0.221 | -0.196 | -0.170 | -0.022 | -0.004 | 0.014 |
|   | 1 | 3 | -0.070 | -0.044 | -0.019 | 0.018 | 0.035 | 0.053 |
|   | 2 | 3 | 0.126 | 0.151 | 0.177 | 0.021 | 0.039 | 0.057 |
| T3 | 1 | 2 | -0.100 | -0.068 | -0.037 | -0.414 | -0.368 | -0.322 |
|   | 1 | 3 | -0.137 | -0.105 | -0.074 | -0.121 | -0.075 | -0.029 |
|   | 2 | 3 | -0.068 | -0.037 | -0.005 | 0.247 | 0.293 | 0.339 |
| T4 | 1 | 2 | 0.014 | 0.008 | -0.001 | -0.040 | -0.028 | -0.016 |
|   | 1 | 3 | 0.014 | 0.021 | 0.027 | 0.023 | 0.035 | 0.047 |
|   | 2 | 3 | 0.022 | 0.028 | 0.035 | 0.050 | 0.063 | 0.075 |
| T1 | 1 | 2 | 0.071 | 0.107 | 0.142 | 0.200 | 0.233 | 0.265 |
|   | 1 | 3 | 0.122 | 0.157 | 0.192 | 0.065 | 0.097 | 0.130 |
|   | 2 | 3 | 0.015 | 0.050 | 0.086 | -0.168 | -0.135 | -0.102 |
| T2 | 1 | 2 | -0.142 | -0.119 | -0.096 | -0.043 | -0.020 | 0.003 |
|   | 1 | 3 | 0.037 | 0.061 | 0.084 | -0.026 | -0.003 | 0.020 |
|   | 2 | 3 | 0.156 | 0.179 | 0.203 | -0.007 | 0.017 | 0.040 |
| T3 | 1 | 2 | -0.031 | 0.020 | 0.070 | -0.231 | -0.185 | -0.140 |
|   | 1 | 3 | -0.289 | -0.239 | -0.188 | -0.175 | -0.129 | -0.083 |
|   | 2 | 3 | -0.309 | -0.258 | -0.208 | 0.010 | 0.056 | 0.102 |

Three different conditions of valve can be separated at all time segments at the 7th and 6th frequency range for vibration and AE signals respectively. However, in comparing the ability to detect different valve conditions, AE technique outperforms vibration technique by detecting three different valve conditions clearly in 19 time-frequency segments, while the later can only detect those conditions in 17 time-frequency segments. In addition, the vibration technique cannot detect the difference between grease and leakage conditions in 4 time-frequency segments, namely frequency 3 and time segment 4, frequency 4 and time segment 4, frequency 5 and time segment 4, and frequency 6 and time segment 4. In contrast, AE technique can detect the grease and leakage condition better as it only failed to differentiate the two conditions in frequency 3 and time segment 3.

### 5. Conclusions

By comparing the confidence interval of AE and vibration signals before WPT and after WPT, it can be concluded that the ability of vibration and AE signals in identifying the normal, grease and leakage valve conditions improved significantly by decomposing the signals into a smaller frequency range through WPT.

In comparing the performance of the vibration and AE technique, it can be concluded that AE technique performed slightly better in detecting different valve conditions due to its high spatial resolution compared to the vibration technique. For future work, the best feature vectors selected from Tukey test can serve as the input vector for other machine learning procedures to achieve the ultimate goal of automated valve failure detection for reciprocating machines.

### Acknowledgement

The authors would like to extend their greatest gratitude to Institute of Research Management and Monitoring (IPPP), University of Malaya for funding the study under Research Grant No. PS113/2010B. In addition, the authors would like to thank Serba Dinamik Sdn. Bhd. for their industrial and financial support.
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