

Acoustic emission based condition monitoring study of piston rod seals by varying speed and pressure parameters

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ABSTRACT

Seal wear is one of the primitive causes of failure in hydraulic cylinders. Regular visual inspection of seals without affecting the productivity is difficult as the seals are placed internally in the hydraulic cylinder requiring disassembly of the piston. Therefore, condition monitoring is required to assess the current health of the seals. There have been successful attempts made in literature for the assessment of seal quality using acoustic emission-based condition monitoring. However, there have been very few acoustic emission-based condition monitoring studies performed to diagnose the seal failure under varying speed and pressure parameters. Therefore, this study aims at increasing the understanding of seal failure under varying speed and pressure conditions through correlation with the acoustic emission features. Experiments were performed on a hydraulic test rig using unworn and worn piston rod seals. For each seal wear condition, experiments were performed for five strokes at pressure conditions of 10, 20, 30 and 40 bar and piston rod speed of 50 mm/s and 100 mm/s. To reduce the noise from other machine parts in the test rig, the acoustic emission signal of each piston rod stroke was filtered using a bandpass filter. The acoustic emission signal before and after bandpass filtering was analyzed using different acoustic emission time and frequency domain features. For unworn and worn piston rod seal conditions, the acoustic emission features obtained from the acoustic emission signal after bandpass filtering have good separability and low variability when compared to the acoustic emission features obtained from the non-filtered data. Therefore, the acoustic emission-based condition monitoring methodology developed in this study lays a strong

foundation for further research to develop real-time monitoring of the piston rod seal in hydraulic cylinders.

Keywords: Piston rod seals, Acoustic emission, Bandpass filter, Speed and Pressure.

1. INTRODUCTION

Hydraulic cylinders are widely used in offshore oil and gas (O&G) industry for different applications such as material handling, clamping systems and heave compensation. Condition monitoring of hydraulic cylinders is gaining importance in the O&G industry to prevent the failure of any critical part as to minimize unscheduled maintenance. One of the primitive causes of failure in hydraulic cylinders is fluid leakage due to piston rod seal wear. Leakage in hydraulic cylinders can result in lack of force, variation in speed or instability in the system (Zhao et al. 2015). Detection of the very initial stage of piston rod seal wear by the visual inspection method is difficult due to concealment of the piston rod seal in the cylinder (An et al., 2005 & Zhao et al., 2015). Therefore, it is important to detect the piston rod seal wear using sensor-based condition monitoring methods that allow active monitoring of the wear-state of the piston rod seal, and thus preventing fluid leakage.

There has been a number of attempts made in literature to study fluid leakage in hydraulic cylinder using different sensor-based condition monitoring methods. For example, Goharrizi et al. (2010) used a wavelet-based approach for analyzing the pressure signal to detect external leakage from a hydraulic actuator. The pressure signal was decomposed into discrete wavelet coefficients. The root mean square (RMS) value of the level 4 coefficient was observed to be sensitive to diagnose external leakage. The scaled RMS value of the level 4 wavelet coefficient under varying leakage conditions are: no leak=1, small leak=0.95, medium small leak=0.78, medium large leak=0.76, and large leak=0.69. In

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the other work of Goharrizi et al. (2010), the RMS value of the level 2 coefficient was observed to be sensitive to detect internal leakage. To detect normal and internal leakage conditions, a baseline of RMS value 30 was defined. During internal leakage conditions, the RMS values stayed below 30, for 90% of the time. The indices were able to detect external leakage as low as 0.3 L/min and internal leakage as low as 0.2 L/min with sensitivity (probability of detection) of 90%. An et al. (2005) applied the extended Kalman filter technique to the pressure signal to monitor external and internal leakage from a hydraulic cylinder. The residual error feature obtained from monitoring chamber pressure was proposed to monitor fluid leakage. With an increase in leakage the magnitude of the residual error increased proportionally. Tang et al. (2010) used the wavelet method with a backpropagation neural network to determine features from the pressure signal that can be used to monitor fluid leakage from the hydraulic cylinder. The energy feature obtained from the frequency bands after wavelet decomposition was composed in the form of an eigen vector. These eigen vectors were later fed as input to the backpropagation network to classify the faults. Using this method, it was possible to identify non-leakage, mild leakage and severe leakage faults. Similarly, Zhao et al. (2015) used wavelet packet analysis to extract features from the inlet and outlet of the pressure signal that can be used to monitor leakage from a hydraulic cylinder. The displacement signal of the piston rod was also used to monitor severity in leakage. The wavelet packet energy variance, wavelet energy of coefficient 1 in level 4, wavelet entropy feature, pressure rising speed and piston rod stretching speed were proposed to monitor the leakage. Tan et al. (2000 & 2003) used vibration measurements to understand the vibration signatures from reciprocating machinery such as hydraulic cylinders. From the vibration data analysis, it was observed that removal of the piston seal in the hydraulic cylinder studied lead to an increase in amplitude at a frequency of 48.8 Hz and with the piston seal installed in the hydraulic cylinder the frequency peak was observed at 96.6 Hz in the amplitude-frequency spectrum. Chen et al. (2007) studied the seal integrity in the hydraulic cylinder using acoustic emission (AE). Different AE features such as power spectral density (PSD), AE count, AE RMS were used to monitor the internal fluid leakage from the hydraulic cylinder. The AE features based on energy such as RMS were observed to be sensitive compared to other AE features such as AE count or peak of PSD to monitor the internal fluid leakage. The AE RMS feature was observed to be sensitive mainly after leakage rate of 0.3 L/min. At internal leakage rate of 0.35 L/min, the AE RMS value was observed to be 0.02 V and at internal leakage rate of 0.82 L/min, the AE RMS value was observed to be 0.85 V. The correlation coefficient value between AE RMS and internal leakage rate was observed to be 0.9654. There have also been attempts to monitor faults in hydraulic motors using different sensor-based condition monitoring methods. For example, Chen et al. (2008) used the wavelet technique to analyse the AE signal from a hydraulic motor. The wavelet spectrum

analyzed in between 5.5-7 kHz was observed to be sensitive to faults compared to conventional PSD. Also, the RMS feature of the AE signal obtained from wavelet analysis was proposed to monitor piston crack under different flow rates and torque. Ramachandran et al. (2018), used a torque sensor to monitor seal degradation in rotating machinery. Different time domain features were used to monitor seal degradation. RMS, peak, mean and squared mean rooted absolute amplitude features of the torque signal were observed to be sensitive to seal degradation over time. In the other work, Ramachandran et al. (2019) used a multi-layer perceptron network to classify torque features related to unworn, semi-worn, worn and completely failed seal. From literature, we can observe that there have been successful attempts to monitor seal wear in hydraulic cylinders or hydraulic motors using different sensor-based condition monitoring methods. However, there have been limited attempts to monitor seal wear from the hydraulic cylinder under varying speed and pressure parameters. Therefore, in this study, an AE based condition monitoring study is adopted to monitor seal wear in the hydraulic cylinder under different speed and pressure conditions. The AE method is mainly chosen because of its broad frequency range and its ability to diagnose the failure in machine parts at very initial stages (Shanbhag et al. 2019).

To study the seal wear using AE, experiments were performed on a hydraulic test rig at different pressure and speed conditions. Because of noise, generated by components of the test rig other than the piston rod seal, the AE signal from each stroke was filtered using a bandpass filter. The unfiltered and filtered AE signals were analyzed using different AE features to understand the sensitivity of AE features to diagnose the seal wear at varying pressure and speed conditions.

2. METHODOLOGY

2.1. Experimental details

A custom built test rig was used to study the piston rod seal wear at different pressure and speed conditions. As shown in Figure 1-a), the test rig consists of an electro-mechanical cylinder with a hydraulic cylinder head. The leakage observed from the test rig closely replicates the typical leakage that is observed in a hydraulic cylinder. The extension and retraction stroke of the piston rod through the cylinder head is driven by a spindle and nut that converts rotational motion of the servomotor to translational motion of the piston rod. The cylinder head is a pressurized flange that contains three bearing strips to withstand arising transversal loads and seals to prevent fluid leakage (Figure 1-b)). Transversal load was not applied in this study. The pressurized fluid within the cylinder head is supplied through a hydraulic power pack and the pressure is controlled by a pressure control valve. An encoder present in the servomotor enables the monitoring of the piston rod position and the recording of the number of times the piston rod passed

through the cylinder head. The test rig is at rest for one second at the end of each extension and retraction stroke to allow the segregation of sensor signal. The length of the extension and retraction strokes are 600mm.

To perform condition monitoring studies only the top seal from the cylinder head was replaced with unworn and worn seals (Figure 1-b)). The unworn seal had no grooves or scratches (Figure 1-c)), whereas the worn seal had major grooves (Figure 1-d)

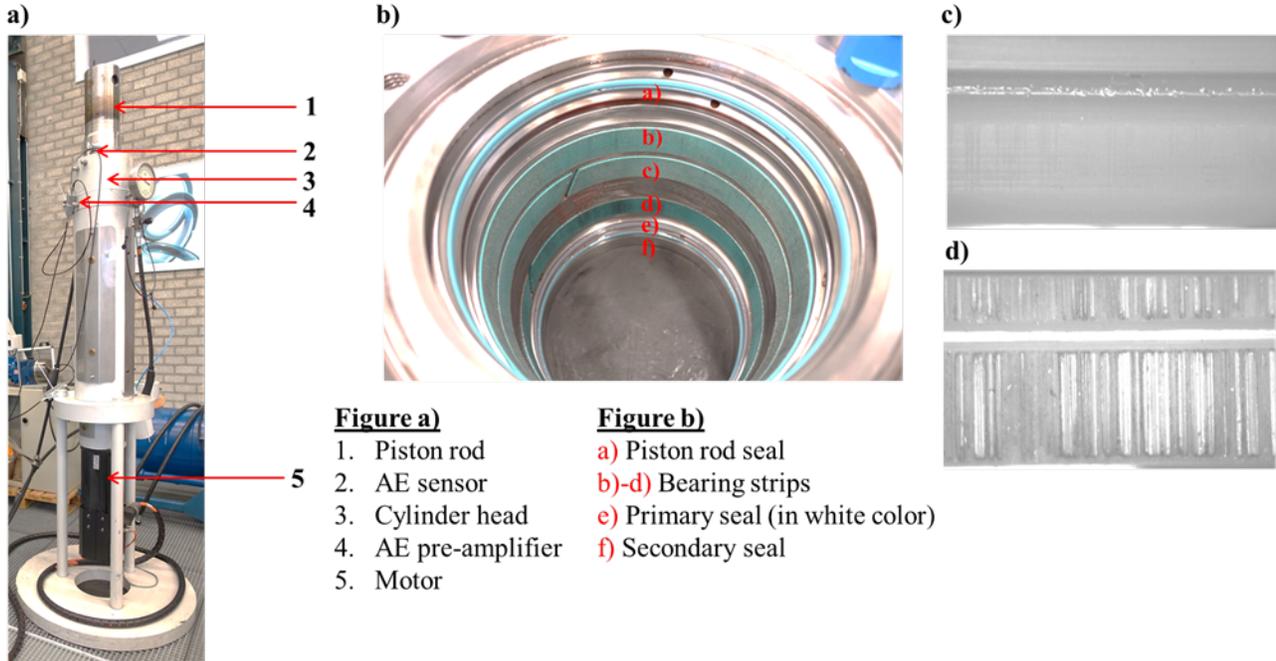


Figure 1. a) Hydraulic test rig b) Piston rod seal and bearing strip arrangement in cylinder head; Microscopic camera images of piston rod seal c) Unworn d) Worn (Note: Instrument used to take close up image of unworn and worn seal: Jenoptik progress speed XT core 3, Pixel size: 3.45 μ .m X 3.45 μ .m)

For each seal condition, experiments were performed at pressure conditions of 10, 20, 30 and 40 bar and speeds of 50 and 100 mm/s. Each experiment was performed for five strokes. Remaining process parameters and experimental details such as fluid type, seal type and seal material are summarized in Table 1.

AE frequency range	50-400 kHz
AE resonant frequency	150 kHz
AE pre-amplifier type	0/2/4 gain

Table 1. Process parameters

Piston rod seal type	Stepseal-2A type (Supplier: Trelleborg Sealing Solutions)
Piston rod seal material	Polyether-based polyurethane elastomer (Grade: Z52)
Seal size	180*195*6.3 mm
Coating on piston rod	Cladded coating of a cobalt based alloy
Fluid	Water glycol
Speed	50 and 100 mm/s
Pressure	10, 20, 30, 40 bar
Stroke length	600 mm
Number of strokes	5
Seal condition	Unworn and worn seal
AE data acquisition	1 MS/s
AE amplifier gain	40 dB

2.2. AE data acquisition

The piston rod seal placed in the cylinder head is in, to a certain extent lubricated, contact with the piston rod during the extraction and retraction stroke (Figure 1 a)-b)). Therefore, the AE sensor is mounted on the piston rod to obtain a good transfer of the AE signal (elastic waves) related to the piston rod seal wear. The AE sensor is fixed to the piston rod using an adhesive bond and industrial duct tape. A mid-frequency range AE sensor (Model: R15 α , Supplier: Physical Acoustics) having an operating AE frequency range of 50-400 kHz is used in this study. The AE sensor is connected to a pre-amplifier (Supplier: Physical Acoustics) using a coaxial cable with BNC (Bayonet Neill-Concelman) and microdot connector. The pre-amplifier is connected to a data acquisition setup using a 5 meter-long cable with BNC connectors. For all the experiments, the AE data acquisition and AE pre-amplifier gain were maintained at 1 MS/s and 40

dB, respectively. The continuous AE signal was recorded for each experiment using AEwin software (Supplier: Physical Acoustics).

To ensure a good signal path to the AE sensor, the Hsu-Nielsen pencil lead break test was performed at regular intervals. If the magnitude of the power spectral density in the AE frequency range of 30-170 kHz (Figure 2) from a pencil lead break was not greater than that of noise (170-500 kHz), then the AE sensor was removed and re-fixed with a sufficient amount of adhesive bond.

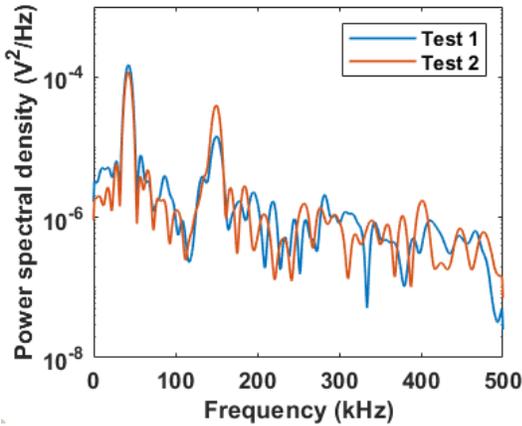


Figure 2. Power spectral density plot of pencil lead break tests (Note: For clarity the y-axis is plotted using log scale)

2.3. AE analysis

The AE signal of the extension and retraction strokes was separated based on the timing of the movement. As the content of the AE signal during extension stroke was similar to that of retraction stroke, only the AE signal related to the extension stroke is used for the analysis. To avoid any starting and stopping phenomena in the continuous AE signal, only the second, third and fourth strokes were used for the AE analysis. Figure 3 represents the methodology adopted for AE data acquisition and AE analysis. As shown in Figure 1-b), the cylinder head contains three bearing strips along the piston rod seal. The continuous AE signal recorded during the experiment may originate from other machine parts such as the bearing strips, piston rod or the two other piston rod seals. Therefore, the power spectrum of the AE signal was initially analyzed to understand the AE frequency related to piston rod seal under investigation. Based on this analysis, the observed AE frequency related to the piston rod seal was used as an input for defining the bandpass filter. The filtered and the unfiltered AE signals were analyzed using various time domain and frequency domain features. The sensitivity of AE features obtained from the unfiltered and the filtered AE signals is studied to understand the AE features that can be used to identify and separate the unworn and worn seal conditions. AE features such as RMS, peak, kurtosis, bandpower, median frequency and mean frequency were used for the analysis. Mean of three strokes and its standard

deviation were calculated for each pressure condition to understand the repeatability of each AE feature that can be used for condition monitoring.

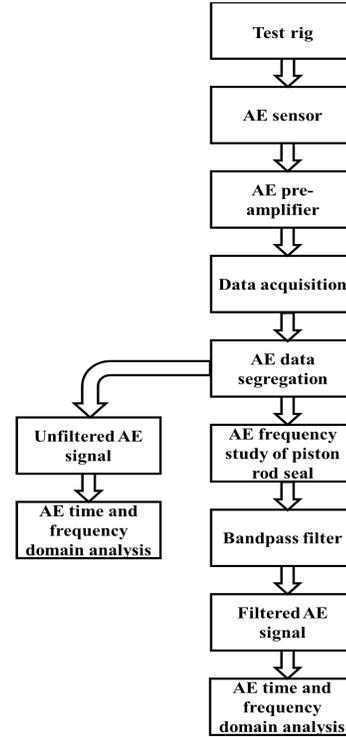


Figure 3. Methodology adopted for AE data acquisition and AE analysis

3. EXPERIMENTAL RESULTS

3.1. Unfiltered AE signal at different speeds

There are different types of AE signals: a) continuous AE signal, b) burst AE signal and c) combination of burst and continuous AE signal (Terchi et al. 2001 & Shanbhag et al. 2020). When the test was performed at 50 mm/s, only a continuous AE signal was observed for the experiments performed using unworn and worn seal (Figure 4 a)-b)). From Figure 4 a)-b), the amplitude of the continuous AE signal for the experiment performed using unworn seal is ≈ 0.2 V and for the worn seal it is ≈ 0.4 V. For the tests performed at 100 mm/s, along with the continuous AE signal, a burst AE signal was observed (Figure 4 c)-d)). Due to non-stationary behavior of the AE signal during the experiments performed at 100 mm/s, it is not clearly possible to identify and separate the amplitude of the AE signal related to unworn and worn seals. The AE burst signals may be caused by other parts of the system, e.g. the bearing strips present in the cylinder head or the spindle present in the test rig. Therefore, to identify the AE signal related to the piston rod seal wear at 50 mm/s and 100 mm/s, bandpass filtering is performed.

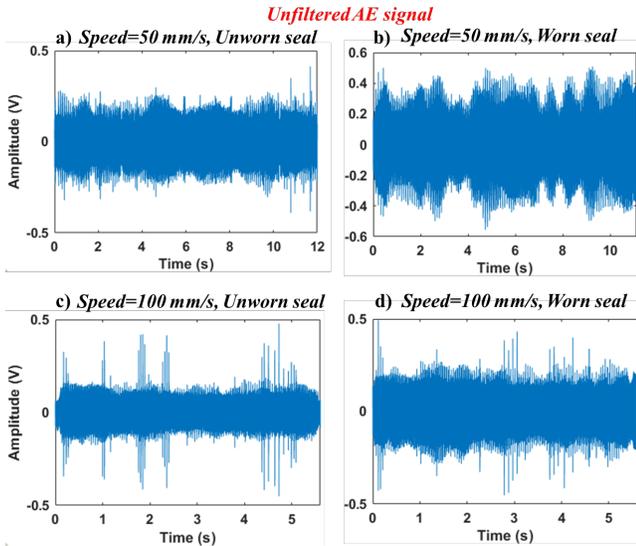


Figure 4. Unfiltered AE signal from test rig observed from a)-b) unworn seal and worn seal at 50 mm/s, c)-d) unworn and worn seal at 100 mm/s. (Pressure=20 bar, stroke number=2, extension stroke AE signal).

3.2. Power spectrum

A power spectrum study is performed to determine the AE frequency related to the piston rod seal wear as input for the bandpass filtering parameters. Figure 5 represents the power spectrum of the AE signal shown in Figure 4 a)-d). Two magnitude peaks in the AE frequency ranges of 0-30 kHz and 50-100 kHz can be observed. These AE magnitude peaks may be caused by other machine parts that are present in the test rig. It is important to note that the AE frequency distribution is nearly consistent except in the AE frequency range of 50-100 kHz. As the piston rod seal (unworn and worn) was the only part in the test rig that was replaced, the AE frequency distribution related to the piston rod seal wear is assumed to be in the AE frequency range of 50-100 kHz. This frequency is thus chosen as the bandpass filter range.

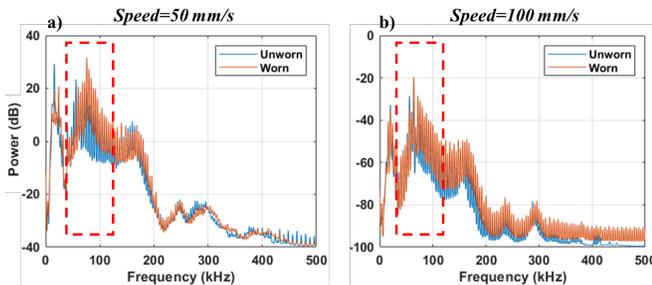


Figure 5. Power spectrum a) 50 mm/s b) 100mm/s. (Pressure=20 bar, stroke number=2, extension stroke AE signal).

3.3. Bandpass filtered AE signal at different speeds

Figure 6 represents the bandpass filtered AE signal in the AE frequency range of 50-100 kHz. Comparing Figure 6 to Figure 4 it can be observed that only the continuous AE signal is observed from the experiments performed at 50 mm/s and 100 mm/s. Also, minimum variation is observed in the AE signal in Figure 6 c)-d) compared to Figure 4 c)-d). From the bandpass filtered AE signal, it is possible to identify and separate the AE signal related to unworn and worn seals at 50 mm/s and 100 mm/s using the amplitude range of the AE continuous signal. At 50mm/s, for the unworn seal the AE amplitude is ≈ 0.2 V, and for the worn seal the AE amplitude is ≈ 0.4 V. Whereas, for the 100 mm/s, for the unworn seal the AE amplitude range is ≈ 0.1 V, and for the worn seal the AE amplitude range is ≈ 0.15 V.

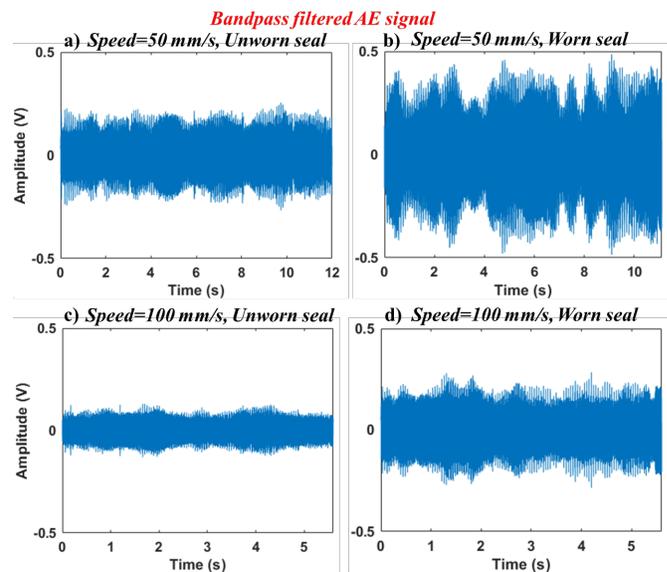


Figure 6. Filtered AE signal from test rig observed from a)-b) unworn seal and worn seal at 50 mm/s, c)-d) unworn and worn seal at 100 mm/s. (Pressure=20 bar, stroke number=2, extension stroke AE signal).

3.4. AE time domain and frequency domain analysis

Figure 7 represents the AE time domain and frequency domain features analyzed based on the unfiltered AE signal. For the experiments performed at 50 mm/s, in the time domain features, the AE RMS and peak features can identify unworn and worn conditions of the piston rod seal in the cylinder head (Figure 7 a), c)). Similarly, for 100 mm/s, the AE RMS and kurtosis features can identify the difference between the unworn and worn seals. However, the separability between the AE features (RMS and kurtosis) for the unworn and worn piston rod seals is low (Figure 7 a)-b)). In the frequency domain features for the experiments performed at 50 mm/s, AE bandpower, median frequency and mean frequency features can identify the unworn and worn piston rod seal conditions in the cylinder head (Figure 7 d)-

f)). The separability of the AE bandpower feature between unworn and worn piston rod seals is low. Similar behavior is also observed for the AE frequency domain features for the experiments performed at 100 mm/s (Figure 7 d)-f)).

Figure 8 represents the AE time domain and frequency domain features analyzed using the bandpass filtered AE signal. For the experiments performed at 50 mm/s, in the AE time domain features, the AE RMS, peak and kurtosis can identify and separate the AE features related to unworn and worn piston rod seals in the cylinder head (Figure 8 a)-c)). Among the AE frequency domain features, AE bandpower and mean frequency can identify and separate the unworn and

worn conditions of the piston rod seal in the cylinder head. However, the separability between the unworn and worn seals for the AE bandpower feature is low compared to the AE mean frequency feature (Figure 8 d)-e)). For the experiments, performed at 100 mm/s, in the AE time domain feature, the AE RMS and peak features can identify and separate the unworn and worn conditions of the piston rod seal in the cylinder head (Figure 8 a), c)). Among the frequency domain features, the AE bandpower, mean frequency and median frequency features can identify and separate the unworn and worn conditions of the piston rod seal in the cylinder head (Figure 8 d)-f)).

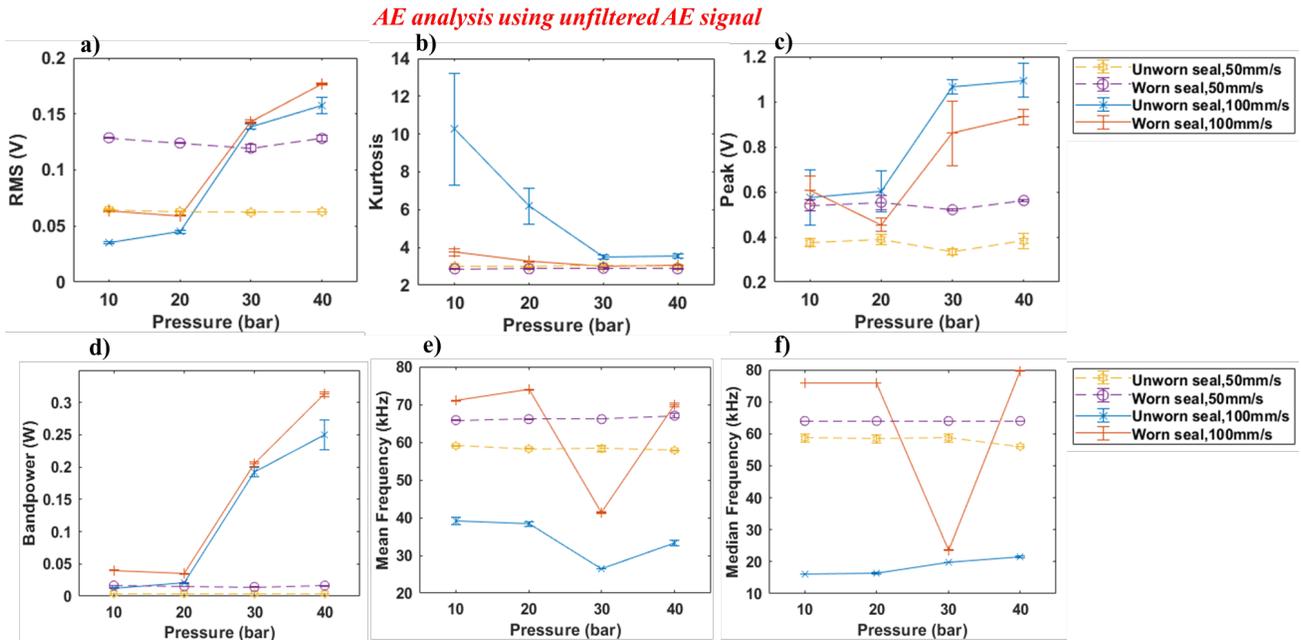


Figure 7. AE time domain features from unfiltered AE signal a) RMS b) Kurtosis c) Peak d) Bandpower e) Mean Frequency f) Median Frequency

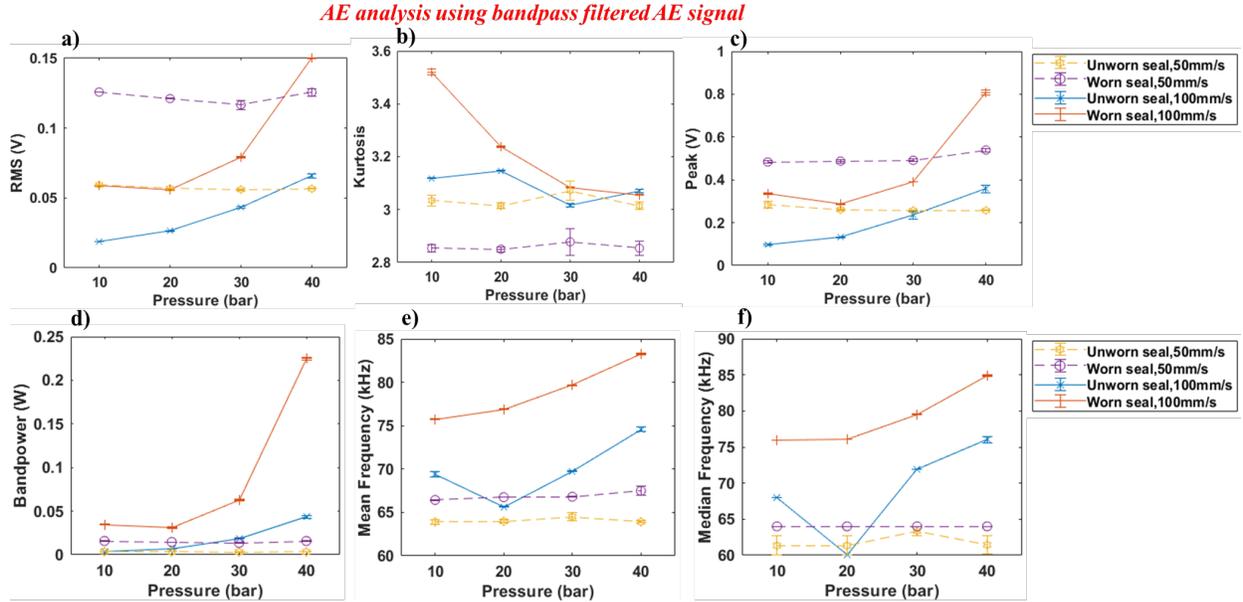


Figure 8. AE time domain features from bandpass filtered AE signal a) RMS b) Kurtosis c) Peak d) Bandpower e) Mean Frequency f) Median Frequency

4. DISCUSSION

Table 2 represents the summary of AE features analyzed using unfiltered and bandpass filtered AE signals. From Figure 7 and Figure 8, it is clear that, for the time and frequency domain features, the separability to identify AE features from bandpass filtered AE signal for unworn and worn seals is higher compared to the AE features analyzed using the unfiltered signal. This is mainly because in the bandpass filtered AE signal there is a minimum interference of AE frequencies related to other parts present in the test rig (Eftekharijad et al. 2011). The higher separability of the AE features for the unworn and worn piston rod seal also indicates better sensitivity and reliability. For the experiments performed at 50 mm/s, the AE features are nearly stable for all the pressure conditions. Whereas, for the experiments performed at 100 mm/s, the AE features tend to get unstable with a change in pressure. This unstable behavior of AE features can be attributed to the higher stress generated on the piston rod seal due to the combined effect of pressure and speed. However, irrespective of the speed and pressure conditions, the AE features can clearly identify and separate the AE features related to unworn and worn piston rod seal. For the AE features obtained from the bandpass filtered AE signal (Figure 8 a), c)-f)), the value of RMS, peak, bandpower, mean frequency and median frequency feature for the worn seal is greater than that of the unworn seal. This is due to the unstable behavior in the cylinder head caused by fluid leakage which results in increase in amplitude and power of the AE signal (Figure 5 and Figure 6). Compared to the condition monitoring studies performed by Zhao et al. (2015) using a pressure sensor and Tan et al. (2003) using a vibration sensor, the energy value of the AE signal tends to increase in our study for the worn piston rod seal when

compared to the unworn piston rod seal (Figure 8-a)). This is likely due to the high working frequency range of the AE sensor which makes it sensitive to the noise generated by the leakage in the cylinder head (Chen et al. 2007). A linear increase can also be observed with the increase in pressure for AE RMS, peak, bandpower, mean frequency and median frequency (Figure 8). This can be attributed to the higher friction generated between piston rod seal and piston rod and to the increase in leakage of oil from the test rig with the increase in pressure (Chen et al. 2007). AE RMS, peak and mean frequency features had higher separability for unworn and worn seals at all the pressure and speed conditions than the other AE features (Table 2).

	Unfiltered AE signal		Bandpass filtered AE signal	
	50 mm/s	100 mm/s	50 mm/s	100 mm/s
Speed				
RMS	✓	✓*	✓	✓
Kurtosis	✗	✓*	✓	✗
Peak	✓	✗	✓	✓
Bandpower	✓*	✓*	✓*	✓
Mean frequency	✓	✓	✓	✓
Median Frequency	✓	✓	✓*	✓

✓ - Can identify unworn & worn seal ✗ - Cannot identify unworn & worn seal
 ✓* - Low separability between the AE features for unworn and worn seal.

Table 2: Summary of AE features

5. SUMMARY

This study investigated the AE features that can be used to detect piston rod seal wear at different pressure and speed conditions in a hydraulic test rig. As the AE signal may originate from different machine parts of the test rig, a bandpass filtering technique was used to filter the AE signal generated by the piston rod seal and rod surface interaction.

1. From the AE power spectrum, the AE frequency range for the piston rod seal wear was observed to be in the AE frequency range of 50-100 kHz
2. The AE time domain features obtained from bandpass filtered AE had higher separability for unworn and worn seal when compared to the AE time domain features obtained from unfiltered AE signal.
3. AE RMS, peak and mean frequency features obtained from the bandpass filtered AE signal had higher separability between the unworn and worn seal for all the pressure and speed conditions than the other AE features.

The higher sensitivity and reliability of the AE features observed for AE RMS, peak and mean frequency to identify the unworn and worn piston rod seal in the test rig indicate that these features could be used for real time monitoring of the piston rod seals in hydraulic cylinders in the offshore O&G industry.

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