Diagnostics of seal and rod degradation in hydraulic cylinders using acoustic emissions

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Abstract

External leakage from hydraulic cylinders is of a major concern for the offshore oil and gas industry. This occurs mainly as a result of physical damage to the piston rod or due to degradation of the piston rod seals. Numerous studies have been conducted to diagnose leakage from hydraulic cylinders due to seal failure using fluid, pressure, accelerometer or acoustic emission-based condition monitoring techniques. However, very few attempts have been made to diagnose multiple faults in hydraulic cylinders at the same time. Therefore, in this study, acoustic emission-based condition monitoring technique is used to detect and separate acoustic emission features due to different faults that are observed in hydraulic cylinders. An experimental study was performed on a test rig using water glycol as hydraulic fluid. Experiments were performed with different combinations of seals (unworn, semi worn and worn seals), and piston rods (unworn and worn). Acoustic emission features such as root mean square, peak, mean, kurtosis, skewness, mean frequency, median frequency and bandpower were used to identify seal and rod conditions. By using acoustic emission median frequency and mean frequency features it was possible to detect and separate leakage, and seal and rod degradation in the test rig over a large range of hydraulic working pressures. This study indicates that acoustic emission monitoring can be a strong basis for future research to identify and segregate other types of faults that are observed in hydraulic cylinders.

Keywords: Hydraulic cylinder, Leakage, Seals, Piston rod, Acoustic emission, and Mean-Frequency.

1. Introduction

Fluid leakage from the hydraulic cylinders is a major concern for the offshore oil and gas (O&G) industry. Fluid leakage from hydraulic cylinders may arise due to piston rod seal failure or physical damage to the piston rod. Untimely failure of the piston rod or its seals can be catastrophic in nature for the O&G industry as it may lead to fluid spill in sea, machine downtime, and maintenance cost (Ramachandran et al., 2018). Visual inspection of the piston rod seal quality at regular intervals is tedious as the piston rod seal is placed internally in the cylinder head. Therefore, sensor-based condition monitoring is required for continuous monitoring of the health of the piston rod and its seals.

In the literature, numerous condition monitoring studies have been conducted using different sensors to monitor fluid leakage from hydraulic cylinders. An et al. (2005), used pressure sensors to monitor the internal and external leakage. Residual pressure error obtained from the external Kalman filter technique was proposed as a feature to diagnose faults causing leakage. Tang at al. (2010) applied wavelet transform and back propagation neural technique to the pressure signal to segregate features related to no leakage, moderate leakage and severe leakage. Goharizzi et al. (2010 & 2011), applied a multiresolution technique to decompose the pressure signal into high frequency (approximate) and low frequency (detail) wavelet coefficients. Root mean square (RMS) of level 4 approximate coefficient and level 2 detail coefficient was proposed as features to monitor external and internal leakages, respectively. This proposed technique is sensitive to diagnosing external leakage as low as 0.3 L/min and internal leakage as low as 0.2 L/min. Zhao et al. (2015), monitored displacement signals, inlet pressure signals and outlet pressure signals of a hydraulic cylinder to determine features that can be used to diagnose leakage at very initial stages. The wavelet packet energy variance feature was observed to be very sensitive to the leakage. Tan et al. (2000 & 2003) monitored water leakage from the water hydraulic cylinders using vibration sensors. The vibration energy (dBV_{rms}) feature was proposed to monitor the change in loading conditions and increase in piston seal wear. Chen et al. (2007) used acoustic emission (AE) time domain features and power spectral density (PSD) to monitor water leakage from a water hydraulic cylinder. The AE energy feature was observed to be sensitive to internal leakage compared to the AE RMS and PSD. From literature we observe that numerous studies have been performed to monitor seal degradation using different sensor technologies. However, few attempts have been made to monitor multiple faults in hydraulic cylinder simultaneously. Therefore, in this study, piston rod seal and piston rod surface degradation are monitored based on AE measurement. The AE sensor is preferred in this study mainly because of its high frequency range, which makes it suitable to study the localized dynamic process, while largely being unaffected by the machine noise (Miller et al., 1987 and Shanbhag et al., 2017).

In this study, a series of experiments were conducted on a test rig using a combination of different piston rod seal conditions (unworn, semi-worn and worn) and rod conditions (unworn and worn). For each test, experiments were performed using different pressure conditions. The AE signal of each stroke obtained from the test was analyzed using different statistical features such as RMS, peak, mean, kurtosis, skewness, mean-frequency, median-frequency and bandpower.

2. METHODOLOGY

2.1. Experimental details

Experiments were performed on a custom-built test rig to monitor the piston rod seal and piston rod degradation based on AE measurements. The test rig consists of an electromechanical cylinder with a hydraulic cylinder head to study the fluid leakage conditions (Figure 1-a)). The piston rod and the cylinder head in the test rig are designed to simulate the conditions of a hydraulic cylinder. The extension and retraction stroke in the electromechanical cylinder are driven by a spindle and a nut, that converts the rotational motion of the servomotor to translational motion of the piston rod. The piston rod passes through a pressurized flange that contains bearing strips and seals, that are normally applied in the hydraulic cylinder head (Figure 1-c)). The piston rod seals in the cylinder act as fluid sealing and three bearing strips in between the piston rod seals are placed to withstand the arising transversal loads. Transversal loads were not applied in this test setup. The hydraulic power pack present in the test rig supplies pressurized fluid to the flange. Pressure in the test rig is controlled through a pressure control valve (Figure 1-b)). The piston rod position in the test rig is controlled by an encoder in the servomotor. The servomotor encoder also records the number of times the piston rod passes through the pressurized flange. The system is at rest for one second at the end of each extension and retraction stroke. To perform condition monitoring studies, only the upper piston rod seal was replaced with unworn, semi-worn and worn piston rod seals (seal type: Stepseal-2A; supplier: Trelleborg sealing solutions). The unworn seal had no grooves, the semi-worn seal had minor grooves and the worn seal had major grooves (Figure 2-a). The unworn piston rod had no scratches (Figure 2-b) while the worn piston rod had severe scratches (Figure 2-c). In this study, fluid leakage was defined when fluid was visible on the piston rod surface. Fluid leakage was not observed for the experiments performed with unworn piston rod seal. Whereas, fluid leakage was observed for all the experiments performed with semi-worn and worn piston rod seals (Figure **1**-d)). Currently, there is no standard quantification technique, to measure fluid leakage from the piston rod surface. Therefore, AE features are qualitatively correlated with the piston rod seal wear and piston rod wear.

Condition monitoring experiments in this study consist of two phases. In the first phase experiments were performed using unworn piston rod and different piston rod seal conditions such as unworn, semi-worn and worn piston rod seals. In the second phase, experiments were performed using worn piston rod and different seal conditions such as unworn and semi-worn piston rod seals. For each seal condition, experiments were performed for five strokes at pressure conditions of 10, 20, 30 and 40 bar. A stroke consists of extension and retraction of piston rod for 600 mm in both directions. Process parameters such as speed and fluid type were kept constant throughout the study and its details are summarized in Table 1. In this study, fluid leakage was observed for the all the experiments performed using semi-worn and worn piston rod seals.

Seal size	180*195*6.3 mm^3	
Oil	Water glycol	
Speed	100 mm/s	
Pressure	10, 20, 30, 40 Bar	
Stroke length	600 mm	
Number of strokes	5	
AE sampling frequency	1 MS/s	
AE amplifier gain	40 dB	
Type of test	***Phase 1-Seal wear study***	***Phase 2-Rod wear study***
Rod Type	Unworn	Worn
Seal condition	Unworn, semi-worn & worn.	Unworn & semi-worn.

Table 1. Experimental and process parameter details.

2.2. Data acquisition details

As shown in Figure 1-b), as the piston rod is in direct contact with the piston rod seal, the AE sensor was placed on the piston rod using adhesive bond and industrial duct tape to secure high AE data acquisition. The AE sensor used in this study was a mid-frequency range resonance sensor (Type: R15α, Supplier: Physical Acoustics), having an operating AE frequency range of 50-400 kHz and AE resonant frequency of 150 kHz. The AE sensor was connected to a selectable gain pre-amplifier (Type: 0/2/4 selectable gain, Supplier: Physical Acoustics) with selected gain of 40 dB. The pre-amplifier was connected to a channel in the data acquisition setup using a 5-meter-long cable. For each experiment, continuous AE data acquisition was performed at sampling frequency of 1 MS/s.

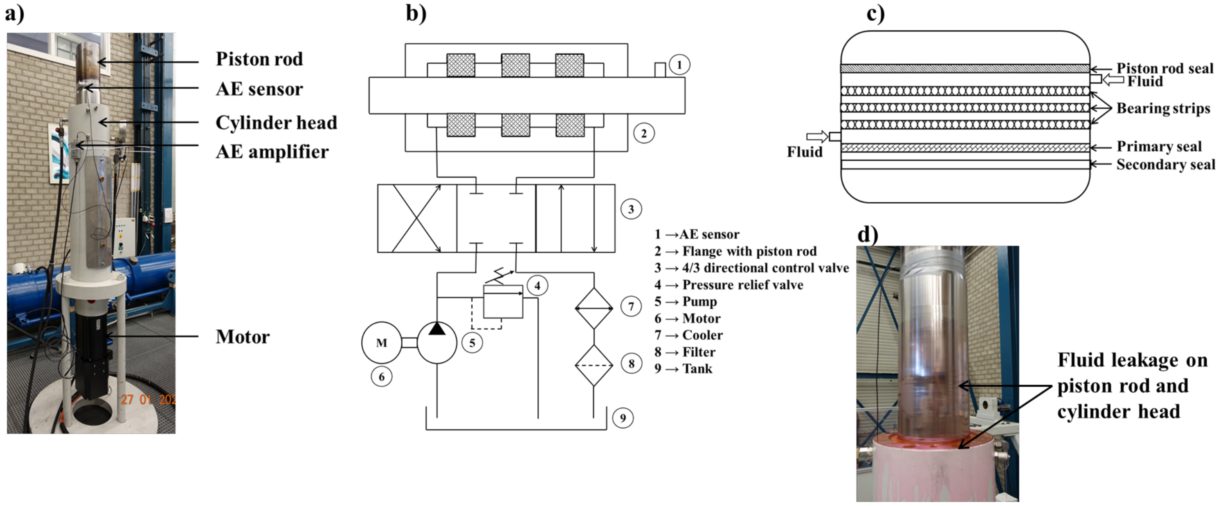

Figure 1. a) Hydraulic test rig, b) Circuit diagram of hydraulic test rig, c) Schematic front view of piston rod seal and bearing strips arrangement in the cylinder head, d) Fluid leakage on piston rod surface and cylinder head.

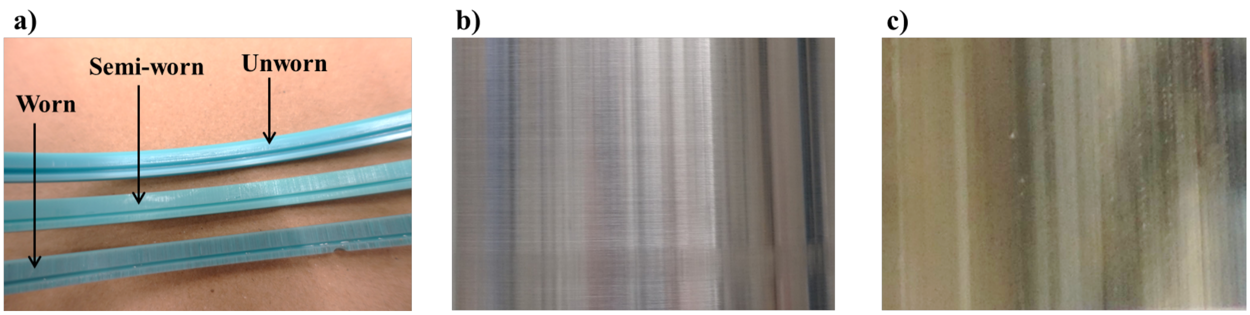

Figure 2. a) Different seals used in the study, close up picture of b) Unworn rod, c) Worn rod.

2.3. Pencil lead break test

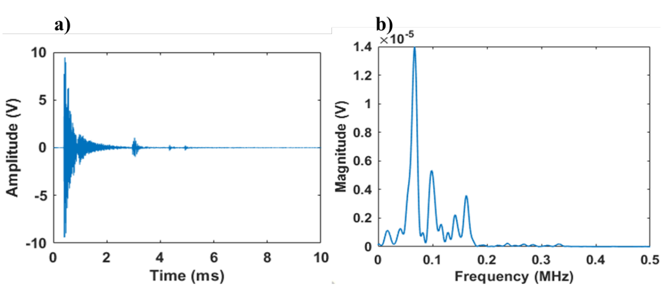

Figure 3. AS signal from pencil lead test a) time domain, b) frequency domain.

To verify the acoustic transfer function between the AE sensor and the piston rod, Hsu-Nielsen pencil lead break test was performed at the start of each experiment. The pencil lead break test was performed on the piston rod by using a 2H pencil lead of 0.5 mm in diameter. From the AE signal represented in the Figure 3-a), the amplitude of noise in between 0-0.25 s and 5.5-10 s is negligible compared to the maximum amplitude of the AE burst signal observed due to fracture of pencil lead in between 0.25-5.5 s. The small AE burst signal in between 3-5.5 s indicates multiple low intensity fractures of pencil lead towards the end of the test. From the frequency-magnitude plot of the AE signal represented in the Figure 3-b), the AE peaks are dominant between 0.025 MHz and 0.2 MHz. If similar AE amplitude and frequency distribution was not observed during the pencil lead break test, the AE sensor was removed and reattached with adhesive bond.

2.4. AE analysis

At the end of the extension and retraction of the rod, there was a pause of one second. Based on this timing, the AE signal due to extension and retraction of the piston rod was segregated and thus similarly each stroke was segregated. As the behavior AE signal of an extension stroke was similar to that of AE signal from a retraction stroke, only the AE analysis from extension strokes is presented in this paper. The AE signal from all five strokes was analyzed. The AE signal was analyzed using AE time domain and frequency domain features such as root mean square (RMS), mean, peak, kurtosis, skewness, mean frequency, median frequency and bandpower (Table 2). The AE time domain and frequency domain features were calculated using inbuilt MATLAB functions (Central tendency and dispersion., 2020, Descriptive statistics., 2020 and Statistics., 2020). To understand the repeatability of these AE features, mean of the standard deviation was calculated.

Root mean square (RMS)	$x_{rms} = \frac{\sum_{n=1}^{N} x\,(n)^2}{N}$
Mean	$x_m = \frac{\sum_{n=1}^{N} x\,(n)}{N}$
Peak (max)	$x_p = \max\lvert x(n)\rvert$
Standard deviation	$x_{std} = \sqrt{\frac{\sum_{n=1}^{N}(x(n) - x_m)^2}{N-1}}$
Skewness	$x_{skew} = \frac{\sum_{n=1}^{N}(x(n) - x_m)^3}{(N-1)x_{std}^3}$
Kurtosis	$x_{kurt} = \frac{\sum_{n=1}^{N}(x(n) - x_m)^4}{(N-1)x_{std}^4}$
Mean frequency	$x_{meanf} = \frac{\sum_{k=1}^{K} f_k s\,(k)}{\sum_{k=1}^{K} s\,(k)}$
Median frequency	$x_{med} = \frac{1}{2}\sum_{k=1}^{K} s\,(k)$
Bandpower	$x_{BP} = \sum_{l=f_1}^{f_2} P_l$

Table 2. Mathematical equation of features used for AE analysis (Binsaeid et al., 2009, Lei et al., 2008 and Phinyomark et al. 2012).

Where, x (n) represents signal series for n=1, 2,….N, N represents number of data points, s (k) represents spectrum for k=1,2…K, K represents number of spectrum lines, f_k represents frequency value of the kth spectrum line, P_l represents average power for l=1,2,…L, L represents number of columns and, f_1, f_2 represent the lower and upper limits of the frequency band respectively.

3. RESULT AND DISCUSSION

3.1. AE signal from different seal and rod conditions

To understand the behavior of the AE signals related to phase 1 (seal study) and phase 2 (rod study) experiments, the AE signal from the extension stroke was analyzed. Figure 4 and Figure 5 represent the AE signal from the phase 1 and phase 2 experiments. There are three 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). From Figure 4 a) - c), along with the continuous AE signal, the burst AE signal can also be observed from the experiments performed using unworn, semi-worn and worn piston rod seals. The continuous AE signal is generated mainly due to friction between the piston rod and its seal. The burst AE signal that is generated is likely due to noise generated from the strips in the cylinder head and rotation of the spindle in the test rig. The amplitude of continuous AE signals from the semi-worn and worn seal (0.2 V) are higher compared to that of unworn seal (0.1 V). As noted in Section 2.1, fluid leakage was observed for the semi-worn and worn seal conditions. Therefore, by using the AE amplitude feature from the continuous signal, it is possible to determine when the AE signal was generated due to non-leakage and leakage conditions. However, only a small difference can be observed from the amplitude feature of the continuous AE signal due to unworn and worn rod –see Figure 5 a) - b). Therefore, to understand the AE features that can be used to segregate different seal and rod conditions, the AE signal is further analyzed using different AE time and frequency domain features.

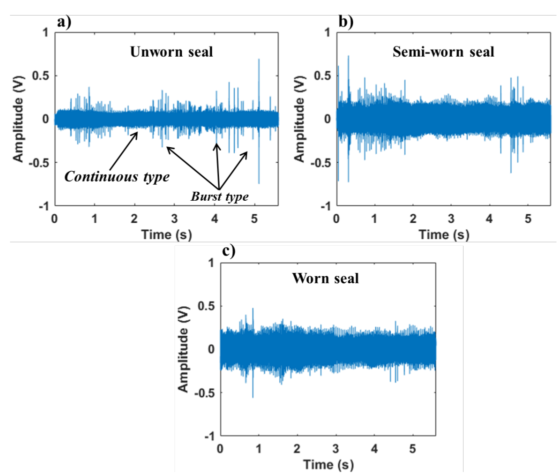

Figure 4. AE signal due to a) unworn seal, b) semi-worn seal, c) worn seal (Unworn rod, Pressure=10 bar, Stroke number=1, extension of rod).

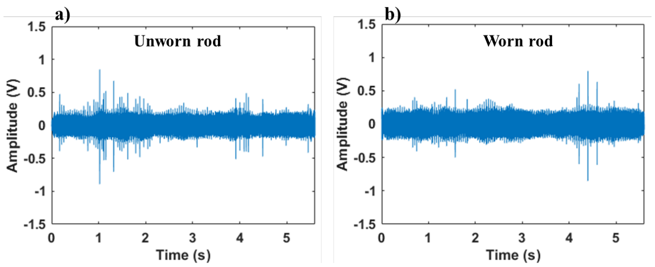

Figure 5. AE signal due to a) Unworn rod, b) Worn rod (Semi-worn seal, Pressure=10 bar, Stroke number=5, extension of rod).

3.2. AE time and frequency domain feature analysis

3.2.1. Unworn rod with different seal conditions

Figure 6 represents the AE signal analyzed of the phase 1 (Seal wear study) experiments using different time and frequency domain features. From the time domain features analyses depicted in Figure 6 a) - e), it is not possible to clearly identify and separate the AE features related to unworn, semi-worn and worn seal. However, the AE skewness feature can identify and separate the non-leakage (unworn seal) and leakage (semi-worn and worn seal) states. In the AE frequency domain feature analysis, AE bandpower, AE median frequency and AE mean frequency features can identify and separate the non-leakage (unworn seal) and leakage (semi-worn and worn seal) states –see Figure 6 f) - h). At 10, 20 and 30 bar pressure for semi-worn and worn seal, the AE bandpower feature is nearly the same. Whereas, for all the pressure conditions, the AE median frequency and AE mean frequency can identify and separate the AE feature related to unworn, semi-worn and worn seals, i.e. all three seal degradation conditions. For all the pressure conditions, the standard deviation is negligible for the AE mean frequency compared to the AE median frequency. The small standard deviation for the AE mean frequency indicates its robustness to be used as condition indicator to determine the condition of the piston rod seal for all pressure conditions.

3.2.2. Unworn rod vs worn rod

Figure 7 depicts the AE signal analyzed for phase 2 (Rod wear study) experiments (non-leakage conditions) using time and frequency domain features. In time domain, the kurtosis and skewness features can identify and separate the unworn and worn rod conditions under the non-leakage condition for all the tested pressure conditions –see Figure 7 d) - e). In frequency domain, the bandpower, mean-frequency and median frequency features can identify and separate the unworn and worn rod conditions under the non-leakage condition for all the tested pressure conditions –see Figure 7 f) - h). Whereas, only median frequency and mean frequency can identify and separate the AE features related to unworn and worn rod conditions under the leakage condition for all the tested pressure conditions –see Figure 8 g) - h).Similar to the phase 1 (Seal wear study) experiments, minimal standard deviation can be observed for the AE mean frequency feature at all the pressure conditions –see Figure 7 - h) and Figure 8 - h). This indicates that the AE mean frequency condition indicator is capable of separating unworn and worn rod conditions under non-leakage and leakage conditions while being robust to changes in working pressure.

3.2.3. Robust condition indicator for hydraulic cylinder

AE Features	Seal wear study		Rod wear study	
	Leakage identification	Leakage identification due to semi worn & worn seal	Without leakage	With leakage
RMS	No	No	No	No
Peak	No	No	No	No
Kurtosis	No	No	No	No
Mean	No	No	Yes	No
Skewness	Yes	No	Yes	No
Median Frequency	Yes	No	Yes	Yes
Mean Frequency	Yes	Yes	Yes	Yes
Bandpower (50-290 kHz)	Yes	No	Yes	No

Table 3. Summary of AE features that can be used to monitor seal and rod wear.

In this study, for the experiments conducted at 100 mm/s, there was noise from different sources such as bearings that are presents in the cylinder head and from the spindle that is connected to the cylinder head. Despite these noise sources from the test rig, the AE mean frequency condition indicator was observed to be robust at all the pressure conditions in indicating and separating the non-leakage condition due to unworn seal and leakage condition due to semi-worn and worn seals (Figure 6-h)). Also, the AE mean frequency feature was observed to be robust in identifying and separating the unworn and worn piston rod under the non-leakage and leakage conditions (Figure 7-h) and Figure 8-h)). Therefore, from this study, the AE mean frequency feature is proposed as robust condition monitoring indicator in identifying seal and rod wear in hydraulic cylinders (Table 3). The developed methodology can be adopted for practical applications by using stud-mounted AE sensors or by mounting the AE sensors on the clevis part of the hydraulic cylinder.

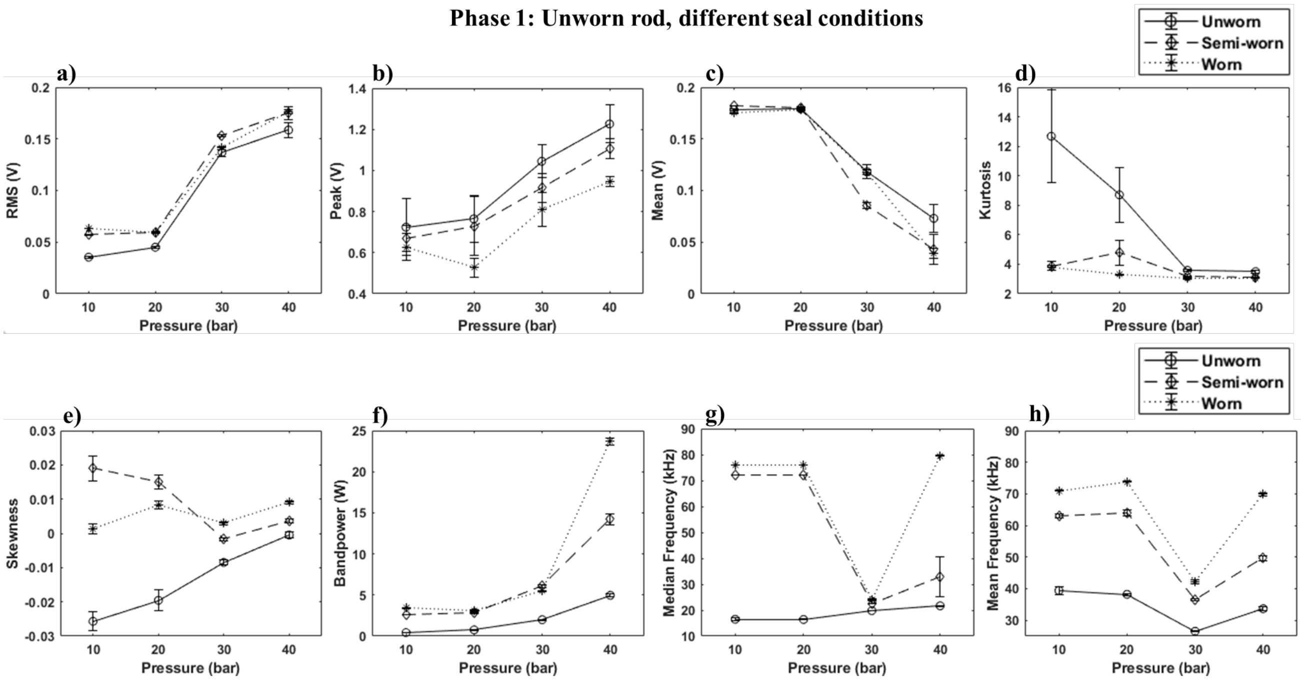

Figure 6. AE time and frequency domain features for the unworn rod with different seal conditions. a) RMS, b) Peak, c) Mean, d) Kurtosis, e) Skewness, f) Bandpower (50-290kHz), g) Median Frequency, h) Mean Frequency.

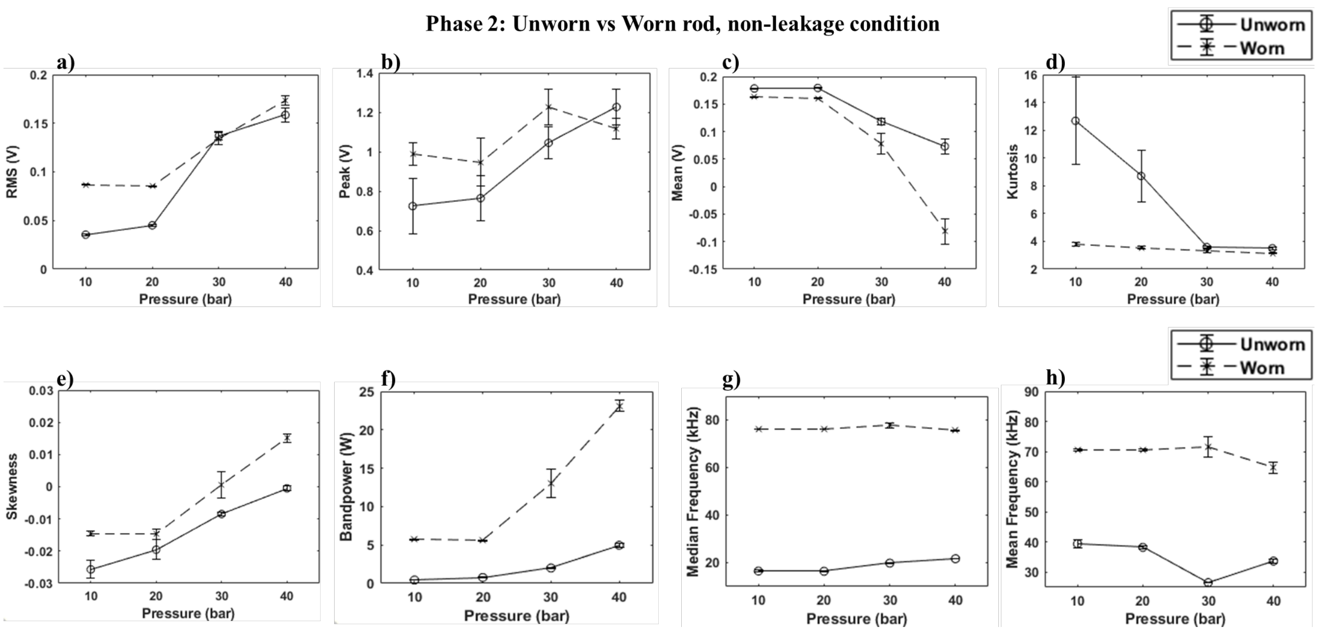

Figure 7. AE time and frequency domain features for the unworn vs worn rod with non-leakage conditions. a) RMS, b) Peak, c) Mean, d) Kurtosis, e) Skewness, f) Bandpower (50-290kHz), g) Median Frequency, h) Mean Frequency.

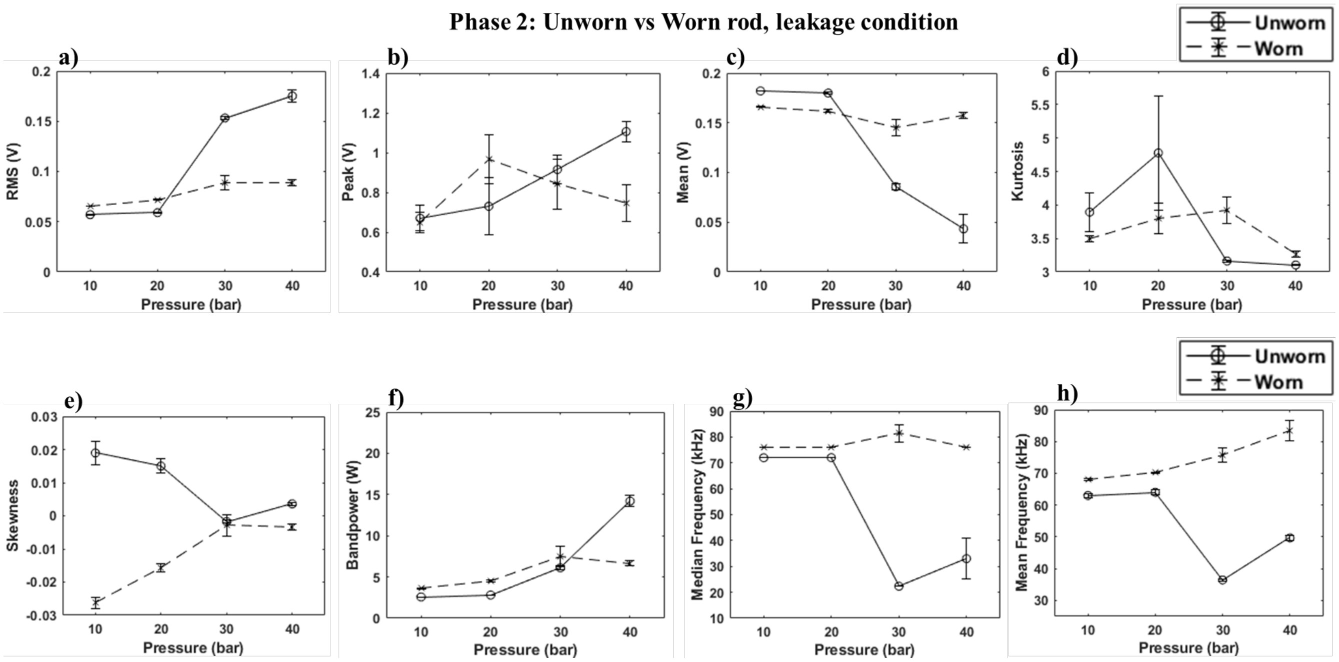

Figure 8. AE time and frequency domain features for the unworn vs worn rod with leakage conditions. a) RMS, b) Peak, c) Mean, d) Kurtosis, e) Skewness, f) Bandpower (50-290kHz), g) Median Frequency, h) Mean Frequency.

4. CONCLUSION

This study investigated simultaneous separation of seal and rod degradation conditions in hydraulic cylinders from AE measurements. Experiments were performed on a test rig using different wear stages of hydraulic cylinder seals and rods.

- Using AE time domain features such as skewness and AE frequency domain features such as bandpower, median frequency and mean frequency it is possible to identify and separate different non-leakage and leakage conditions.
- Using AE time domain features such as mean and skewness, and AE frequency domain features such as bandpower, median frequency, and mean frequency it is possible to identify and separate unworn and worn rod conditions under the non-leakage condition. Under the leakage condition, median and mean frequencies can identify and separate unworn and worn rod conditions.
- Among all the AE features, the AE mean frequency feature had minimal standard deviation while identifying and separating leakage due to semi worn and worn seals, in addition to identifying and separating unworn and worn rod conditions due to non-leakage and leakage conditions.

The preliminary results observed in this study lay a strong basis for future research using AE to identify and segregate other types of faults that are observed in hydraulic cylinders.

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