ABUAD Journal of Engineering Research and Development (AJERD)
Volume 1, Issue 1, 115-123

Adopting Kurtosis for Condition Monitoring of Subsea Production System

Ndubuisi Uchechukwu OKEREKE[1,*], Yahaya Danjuma BABA[1], Adebayo OGUNYEMI[1], John Olusoji OWOLABI[1], Mayowa Adeoye LALA[1]

[1]*Chemical and Petroleum Engineering Department, Afe Babalola University, Km. 8.5 Afe Babalola way, Ado-Ekiti*
`okerekenu@abuad.edu.ng/yahya2k@gmail.com/owolabijohn@abuad.edu.ng/lalamayowaadeoye@yahoo.com`

[*]*Corresponding Author:* `okerekenu@abuad.edu.ng`

Date of First Submission: *28/09/2017*
Date Accepted: *24/10/2017*

Abstract: *Subsea systems and components overtime are susceptible to failures and degradation which if not detected early could cause immense damage to the subsea architecture and result in significant revenue loss in oil and gas production. Within a typical subsea production system (such as the subsea control module), the probability of system failure is distributed in a way that allows condition monitoring techniques/algorithms to detect early malfunction before total failure occurs. This study focused on the application of Kurtosis algorithm to ascertain the probability of failure of a subsea pump device. The Kurtosis algorithm was applied to data acquired for a typical subsea pump as sourced from* [1]. *The vibration data gathered was used to assess the level of degradation of the subsea pump. The subsea multiphase pump considered in the case-study operates at a pressure rating of up to 15,000psi and a differential pressure of about 2,500psi. Data was obtained based on vibration signals on the subsea pump and Kurtosis algorithm was used to evaluate the performance of the subsea pump. Results of this study indicated 94.3% availability of the subsea pump, highlighting that the subsea pump was functioning optimally. This study also identified that industry was geared towards deploying cloud based condition monitoring, thereby making it easy to remotely monitor offshore asset from land based control stations. This study recommended integrating Kurtosis algorithm into some of the future cloud based condition monitoring approaches, considering the robustness of the algorithm. This paper also highlighted the relevance of condition monitoring on other subsea components.*

Keywords: Algorithm, Back pressure, Condition monitoring, Multiphase, Kurtosis

1. INTRODUCTION

1.1 Background/Problem Definition

In order to improve offshore oil and gas asset life and improve production from offshore oil and gas asset, there is the urgent need to improve on maintenance strategies deployed in offshore oil and gas industry. This paper focused on assessing condition monitoring strategies deployed in managing offshore oil and gas assets. Making reference to Figure 1 below, global offshore oil and gas production is projected to supercede 50 MMboe/d beyond 2020 with asset services projected to contribute over 40% of the expenditure [2]. In order to optimize the expenditure for offshore oil and gas production, there is the need ensure deployment of suitable condition monitoring strategy. In this study, Kurtosis algorithm was deployed in carrying out condition monitoring of subsea pump.

Subsea pumps require regular maintenance resulting from general degradation based on the operating conditions of the pump. Such maintenance is carried out at intervals in order to minimize operational breakdown. Basically, a planned maintenance minimises production losses for the company unlike unplanned shut down.

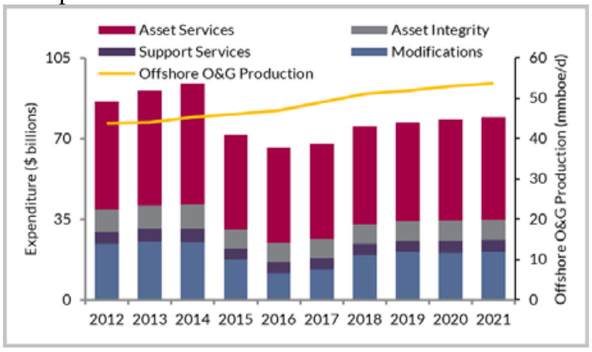

Figure 1:Maintenance, Modification and Operations Market [2]

Typically, an efficient maintenance regime includes a warning system that indicates the need for a planned intervention at a specific time. For instance, in the operation of compressor pumps, some key parameters are monitored by observing the data associated with such parameters, thereby enabling the prediction of the time for maintenance.

This paper focussed on carrying out a contemporary review on condition monitoring techniques and deploying kurtosis in the condition monitoring of the shaft of a sample subsea pump case-study. Subsequent sections of this paper involved the definition of the concept of condition monitoring, the benefits of condition monitoring, an updated review on condition monitoring techniques and a case-study on assessment of subsea pump degradation.

1.2 Definition of Condition Monitoring

This refers to the continued monitoring of the performance of a machine by means of embedded sensors while it is in operation. This mechanism allows information to be obtained externally about the internal order of a machine while still in operation. Condition monitoring of subsea production systems is a recommended practise, which prevents unnecessary losses in production due to system failures.

Subsea pumps are primarily used in subsea to enhance oil recovery in low pressure wells, and to support separation of 3-phase (oil/gas/water phase mixture). Hence, this study focussed on discussing this key component of a subsea system and methods of evaluating its performance while in operation.

The Offshore industry is currently operating at 100% CAPEX utilization, requiring huge capital investment and at the same time must imbibe processes that will ensure compliance with challenging operational demands and stern regulatory requirements [3].

An effective condition monitoring and analytical tool can be deployed to manage the above industry processes and offer performance evaluation of critical devices by detecting early defects and minimize equipment downtime.

1.3 Importance of Condition Monitoring in Subsea Production Systems

The benefits of conducting a condition monitoring program within subsea production operations include;

- Reduction of downtime and increase of operation uptime
- Elimination of accidental failures
- Reduction of general maintenance costs
- Removal of collateral damage
- Improving the overall maintenance strategy
- Supporting downtime optimization as a result of intermittent inspections
- Reduction of the risk of fatigue failure on structural components
- To save overhead costs due to unplanned shutdowns and repairs

1.4 Available Condition Monitoring Methods/Techniques

A condition monitoring system is designed with sensors to perform the function of collecting and analysing information from an operating machine. This arrangement could be either on a permanent or intermittent basis.

The CM (Condition Monitoring) principle of operation is based mainly on identifying a measurable parameter, which will change in value as the machine, or system deteriorates.

Some basic methods for CM include:

- Vibration analysis
- Oil analysis
- Thermography

1.4.1 Vibration Analysis

All rotating machines including subsea pumps vibrate to some extent due to excitation forces such as rotor unbalance, turbulent liquid flow, fluid pressure and machine failure. A machine operating at standard conditions do so at a particular frequency; and traces of fault elements can change this frequency. Vibration analysis uses devices such as accelerometers and proximity probes to monitor these frequency changes resulting in torsional vibrations while conveying significant data information on subsea machine condition to a topside database server. This allows for processing and further intervention steps [4].

Some of the devices can be attached temporarily to a machine so that data retrieval becomes quick and efficient.

Figure 2 illustrates a typical vibration spectrum of a subsea pump with its amplitude varying at different operating conditions [5].

1.4.2 Oil Analysis

This involves the testing of lubricant oil in pumps at regular intervals using spectrographic analysis to detect presence of wear debris from pump materials. This procedure requires that oil sampling, changing and augmentation should be well defined and documented at intervals [5].

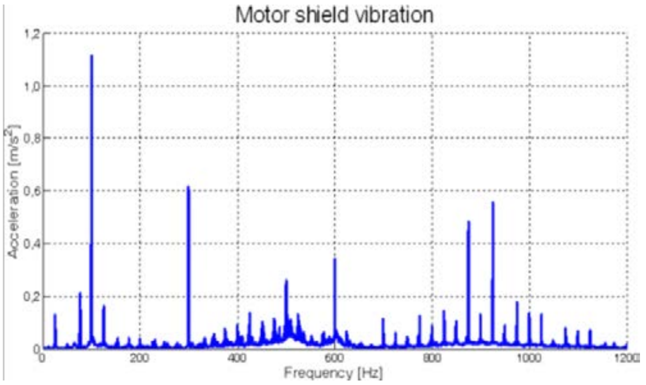

Figure 2: vibration spectrum of a subsea pump [5]

1.4.3 Thermographic Process

This technique is used in quasi-static environments to measure small temperature changes, which reflect machine inefficiency. Efficiency can then be calculated using differential / inlet temperatures and making comparison over time [6].

For CM, thermodynamic method is highly recommended if no temperature or pressure tapping points is required for the monitoring.

1.5 Data processing in CM

Data interpretation is a critical procedure in evaluating performance with defined parameters that will inform operators on possible failure or not. Statistical analysis is required in this process with data acquisition taken at normal operating conditions of the machine.

This forms the basic step in data retrieval processes as subsequent machine evaluations are compared to these initial values.

Parameters to be measured during vibrational analysis include; coefficient of skewness and kurtosis value; these indicate peak vibrational velocity measured in Inches per Second (In/sec) [6]; see Table 1.

Table 1: Condition Log Details for Vibration Analysis [6]

	Acceptable vibration	**Moderate vibration**	**High vibration**	**Damaging vibration**
Data range (In/sec)	< 0.35	0.35- 0.60	0.6- 0.9	>0.9
Action taken	No action	Need for intervention	Shut down	Shut down immediately

Data can also be captured as the resonance half wave - speed Vs the number of impeller vanes.

Typically, vibration signals from subsea equipment can be assessed based on the generic flow chart highlighted in Figure 3.

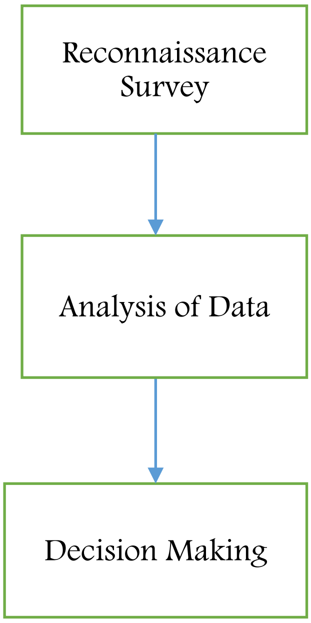

Figure 3: Major phases of condition monitoring application

2. BACKGROUND REVIEW ON BASIS FOR CONDITION MONITORING (CM)

With increasing production from offshore reserves, there is the need to improve on the availability of subsea equipment as studies by [7] suggests that availability of subsea equipment could be as low as 90%.

Availability is defined as:

$$Availability = \frac{MTBF}{MTBF+MTBR} \quad [8]$$

Where MTBF is the mean time before failure otherwise known as uptime and MTBR is the mean time before repair otherwise known as downtime. The reason for this high tendency of un-availability of subsea equipment is associated with the fact that repairs are done easier on the topsides as opposed to the subsea environment where it could be very difficult to assess equipment condition and provide easy repair. Hence, the need for condition monitoring of subsea equipment in order to provide proactive maintenance that will lead to improved availability of subsea equipment.

As a result of wear, subsea pumps often require maintenance at certain regular intervals. Typically, operating conditions of subsea pumps; determines the service interval for subsea pumps. In servicing a subsea pump, there is the need to replace the part of the original pump with a new default spare. Based on [5], an unscheduled maintenance can typically give rise to a downtime ranging from 7 days to up to 8 weeks considering the effect of winter in the event of a rough weather. However, in the case of a planned maintenance, it could be completed within 24 hours. For instance, in the case of a subsea pump giving rise to a production increase of say 5000 bopd at an oil price of 50 USD, the production loss will be at a minimum of $1.7 Million USD with 7 days of shutdown. The production loss could get to a maximum of $14 Million US Dollars for regions where the weather is rough with possible 8 weeks of shutdown. Hence, there is an urgent need to develop proactive condition monitoring strategies that can prevent the loss in production associated with maintenance issues on subsea equipments, especially subsea pump.

Typically, the maintenance can be done based on several strategies [5], as follows:

- "Operate until failure". Giving rise to typically 1-8 weeks of downtime
- "Replace with spares 4th yearly". Based on worst case scenarios analysis
- "Make spare changes on time". With reference to the details of the equipment condition.

2.1 Review on Condition Monitoring (CM) Concept

Condition Monitoring involves equipment surveillance of operational parameters or process variables of industrial machinery to ascertain its health. The key objectives of CM include: 1) Determining the mechanical state of the equipment and 2) Generating trends of the equipment degradation in order to predict failure. With proper condition monitoring of equipment, companies can plan maintenance activities in a convenient manner to minimize NPT (Non-Productive Time).

Condition Monitoring (CM) is basically a predictive maintenance concept and it emerged from an evolution of different maintenance strategies. At the inception of the industrial era, maintenance was viewed as a process that hinders production. The first set of maintenance approaches were based on replacing parts of equipment when they failed or performed below the expected standards, which is not acceptable for production. This approach known as corrective maintenance is in principle a reactive process and therefore very inefficient. Production can be stopped inadvertently and repair activities not planned, leading to a loss in productive time for both tracing of the root cause of the failure and planning the repairs, as well as obtaining the resources for the repairs thereby leading to huge production loss [8].

It is important to note that although maintenance strategies are evolving, corrective maintenance cannot be completely avoided, but can only be reduced to the barest minimum. As at some occasions there will be need to deal with corrective maintenance as a result of equipment failure.

One key CM service offered by Schlumberger is integrity surveillance of risers, flowlines and jumpers [8].

Aker Solutions also recently made major developments in the condition monitoring of subsea equipment. It has its own e-field program, which is based on surveillance of instrumentation, analysis of data, operational optimization and advanced control through intervention in real time, and remote operations [9].

Observing certain key parameters is very relevant in order to be able to efficiently monitor the performance of subsea equipment and plan on-time maintenance. Citing [5], four key parameters that can be monitored are highlighted below:

- Oil consumption,
- Status of Accumulator
- Performance of pump
- Vibration Analysis

2.1.1 Oil Consumption

Typically, the oil consumption within a subsea pump lube oil casing is often increasing with time from an original low value, as the routes of the leakage increases. On some cases, the consumption rate of oil approaches a level where it is difficult to top up the oil consumed adequately, because of the high rate of leakage. Considering that the lube oil used in subsea pumps are basically viscous, the maximum rate of leakage allowed for example on a typical 30 km umbilical is basically in the range of 10 litres per hour [5].

In subsea production systems, subsea pumps are fed from oil tanks on the topside system HPU. In the process of observing the drop in level in these tanks, the oil consumption can be determined. Oil consumption is in practice computed per day, per week and per month [10].

It is important to highlight the influence of power surge in increasing the volume of oil consumed by a typical subsea pump as compared to periods of steady power supply with a relatively regular volume of oil consumed. It is also important to consider this fact during analysis of oil volume consumed for subsea pump operations.

2.1.2 Status of Accumulator

For a typical subsea pump, 8 x 20 litre accumulators are basically designed as the associated accumulators. In the industry, these are used after a shutdown has occurred and the lube oil within the accumulator needs to be re-filled in order to ensure overpressure is maintained. Most accumulators are often designed over-sized with safety margins. However, if say half of the accumulators are no longer functioning properly, then maintaining overpressure during shutdown may no longer be feasible [5].

2.1.3 Performance of Pump

The performance of a typical pump is recognised as η and is computed based on key parameters such as the rate of flow, change in pressure and consumed power as highlighted below:

$$\boldsymbol{\eta = \frac{Q\Delta p}{P}} \quad \textbf{(1)}$$

Where Q is the volumetric flow rate across the pump
Δp is the differential pressure across the pump
P is the power of the shaft that the pump consumes

Typically, the performance of the pump can be observed since the pump flow rate Q can be measured and change in pressure across the pump Δp as well as the pump shaft power can either be measured or estimated [11].

In the industry, a key rule of thumb is to effect maintenance when the subsea pump has reached a certain percentage as compared to its original performance. To enable a basic comparison, the performance measurement is often initially scaled to 100%.

2.1.4 Vibration

Based on [4], vibration analysis is another critical tool for assessing the performance of pumps. Vibration analysis is currently deployed on topsides pump systems; but in deploying vibration analysis in subsea pumps, the sensors are shielded, making them less sensitive to vibration signals as compared to the sensors used on topsides systems that are not shielded. Hence, there is need to improve the sensors deployed for vibration analysis in subsea pumps.

As part of measures to continuously improve maintenance operations practice, operators are currently opting for Integrated Operations Generations 2 (IO) which is a more proactive maintenance approach as highlighted in Figure 4 [12]. This approach involves integrating offshore and onshore support centres in order to provide round the clock surveillance on the sensitive subsea equipment available in the offshore fields.

Based on [13], an operator’s maintenance programme has four objectives:

- To enable realization of the inherent safety and reliability levels of the equipment
- To enable restoration of safety and reliability levels to inherent levels after deterioration has occurred
- To achieve information necessary for design improvement, for items that need design improvement to raise their inherent safety and reliability levels

In Figure 5, a typical proactive and reactive condition monitoring scenario are evaluated, highlighting the disadvantage of the reactive condition monitoring strategy such as corrective maintenance, where there is a sudden change from green (operational mode) to red (failure mode) without notice in the second row as against what was obtained in the proactive condition monitoring approach in the upper row where yellow warning sign enabled on-time intervention thereby preventing a complete failure of the system which typically leads to huge downtime.

2.2 CPM System Visualization

The visualization of CPM System is the most exciting tool for collaboration [12]. It brings the people involved in the problem solving together with a common mental picture. This is highlighted in Figure 6, where an eroded choke within the subsea environment is being evaluated to in order to provide proactive maintenance.

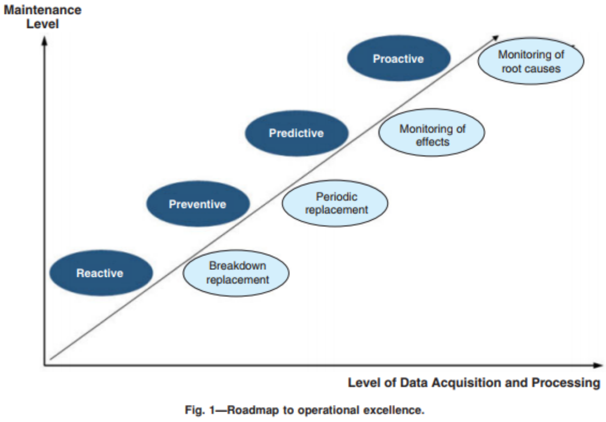

Figure 4: Operational Excellence in Maintenance – Roadmap [12]

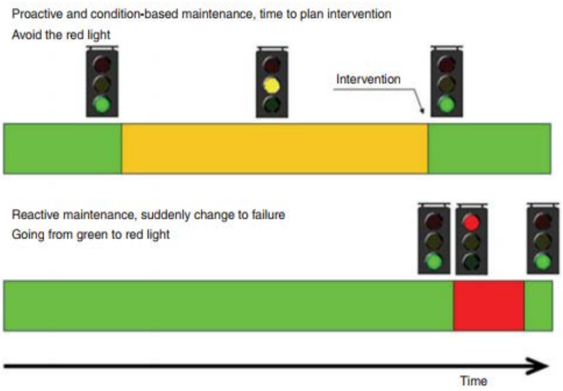

Figure 5: Time to plan for Proactive and CBM during Yellow light [12].

2.3 Condition Monitoring Development in Subsea Production – Phases:

Sequel to the deployment of CM in the oil and gas industry, it has been in use in other industries such as the car manufacturing industry, maritime industry, power and aerospace.

In the maritime industry for instance, it was profitable to keep the vessels in transit as much as possible. Therefore the introduction of condition based maintenance (CBM), supported in minimizing the cumulative repair time at ports.

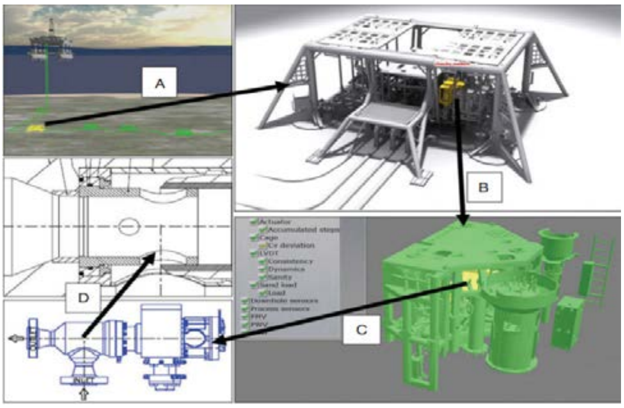

Figure 6: Zooming from an overall view, into an eroded choke [12]

One of the most significant developments in the maritime industry was the development of Technical Condition Index (TCI), which involved a measure for integrity, health and performance based on aggregation of technical, financial and statistical parameters [8]. TCI involves the use of Bayesian network in describing the behaviour of a hierarchical system. The TCIs are calculated from the minimum component level (child) to the maximum level (parent) in order to determine the impact of the child nodes to the parent node and finally providing a top-level status for the whole system.
The computation can be simply described as:

$$TCI_{parent} = \frac{\sum_i^n TCI_i * W_i}{\sum_i^n W_i} \quad (2)$$

Where TCI_i is the TCI of child i, W_i the weight value of child i and n is the number of child nodes. The key advantage of the TCI statistical tool is that it provides information about a system in its entirety instead of only a list of conventional key performance indicators for individual components, which enables a clear understanding of the system status.

With respect to the railway industry, the tendency for degradation and malfunctioning of the train over the life span of the train could reduce the transport efficiency and cause economic losses, especially if not monitored. In typical worse scenarios, it could lead to catastrophe with severe human injuries and possible fatalities for passengers in trains. Therefore, it is very essential to utilize CM techniques in detecting early warnings, in order to avert possible failures due to train accident.

Drawing from other industries as mentioned earlier, such as car manufacturing, railway etc; the subsea industry in recent times has adapted CM strategies in some current offshore oil and gas field developments such as is the case in King field [14] where CM was adapted to monitor the subsea pump behaviour over the life of the field. Based on literature review, key parameters such as; consumption rate of oil, status of accumulator, performance of pump, analysis of vibration signals and the analysis of the profiles of valves can be monitored via algorithms coded into softwares that designed for condition monitoring [9].

There are also prospects of having cloud based condition monitoring which will be basically wireless and involving the use of apps on smart devices to monitor the behaviour of key parameters of production systems that could be based offshore from a control station onshore as highlighted in the works of [15]. These are next generation approaches, which the subsea industry is gradually making efforts to adapt in order to optimize typical maintenance costs by ensuring on-time maintenance.

Based on literature review, the key gap identified is the need for adapting robust methodologies/algorithms which can be built into future condition monitoring systems for monitoring the performance of subsea equipment and that forms a key part of this study.

3. KURTOSIS CONCEPT

Kurtosis is derived from the Greek word: kurtos, which implies "curved" and it is a measure of the "tailedness" of the probability distribution of a typical real-value random variable. It is similar to the concept of skewness. Kurtosis in simple terms is a description of the shape of a probability distribution and in similar manner to skewness, there are different approaches of quantifying it for a theoretical distribution and corresponding ways of estimating it from a sample of a typical population [16].

Citing [17], the standard measure of kurtosis was defined as based on a scaled version of the fourth moment of the data or population. This number relates to the tails of a typical distribution and not its peak; [18] hence, often-time observed characterization as "peakedness" is not correct.

In principle, the kurtosis of a sample univariate normal distribution is 3. It is a common occurrence to compare the kurtosis of any distribution to this value (3). Distributions that have kurtosis value of less than 3 are noted to be distributions with few and less extreme outliers as compared to those of a typical normal distribution. However, this does not imply that such distributions with value less 3 are "flat-topped" as mostly reported [18, 19].

An alternative measure of kurtosis is: the L-kurtosis, which is a scaled version of the fourth L-moment; measures based on four sample population. These are analogous to the alternative measures of skewness that are not based on ordinary moments [19].

The kurtosis is the fourth standardized moment, defined as:

$$\mathbf{Kurt}\,[\mathbf{X}] = \mathbf{E}\left[\left(\frac{\mathbf{x}-\boldsymbol{\mu}}{\boldsymbol{\sigma}}\right)^4\right] = \frac{\boldsymbol{\mu}_4}{\boldsymbol{\sigma}^4} = \frac{\mathbf{E}(\mathbf{X}-\boldsymbol{\mu})^4}{(\mathbf{E}(\mathbf{X}-\boldsymbol{\mu})^2)^2} \qquad (3)$$

Where μ_4 is the fourth central moment and σ is the standard deviation. Numerous letters are used in the literature to denote kurtosis. A very common choice is κ, which is fine as long as it is clear that it does not refer to a cummulative. Other choices include $\gamma 2$, which is similar to the notation for skewness, although sometimes this is instead used to denote excess kurtosis [19].

The kurtosis is bounded below by the squared skewness plus 1 [19]:

$$\frac{\boldsymbol{\mu}_4}{\boldsymbol{\sigma}^4} \geq \left(\frac{\boldsymbol{\mu}_3}{\boldsymbol{\sigma}^3}\right)^2 + \mathbf{1} \qquad (4)$$

Where μ_3 is the third central moment. The lower bound is achieved by the Bernoulli distribution. There is no upper limit to the excess kurtosis of a general probability distribution, and it may be infinite.

3.1 Technical Condition Index

Another major algorithm deployed for condition monitoring is the Technical Condition Index (TCI) which involves using a mathematical model to describe the behaviour of a system by assessing the individual components of a system in a hierarchical tree model format with one or more TCIs and aggregating the statistical result of the individual component from the lowest (child level) to the system level (parent). However, Kurtosis has the advantage of capturing a fourth order level rigorous statistical analysis of the possible degradation of typical equipment. Also, considering the benchmark of < or = 3 used as basis for assessing kurtosis data distribution, the barest minimum of possible odd that can give rise to failure of a system is taken into consideration as compared with other approaches like the TCI (Algorithm).

3.2 RMS (Root Mean Square) Condition Monitoring

Another major approach for current intelligent CM systems is RMS (Root Mean Square) which is an algorithm that measures mainly the amplitude or the root mean square amplitude is defined as the variance of the signal magnitude [20], i.e.

$$\boldsymbol{x_{RMS}} = \sqrt{\frac{\mathbf{1}}{\boldsymbol{T}}}\int |\boldsymbol{x}\ (\boldsymbol{t})|^2 \qquad (5)$$

Where T is the sampled signal duration, and x(t) is the vibration signal. RMS amplitude is resilient to spurious peaks in the steady state operating condition.

The main draw-back of this approach is that it's resilience to picking up spurious peaks is mainly limited to steady state operating condition, while most subsea equipment are on transient operation mode in deepwater offshore fields.

Hence, considering the drawbacks of other possible approaches highlighted in section 3.1 and 3.2, Kurtosis was adopted for this study.

3.3 Application of Kurtosis

The fourth-order moment kurtosis is mostly used in machine condition monitoring as highlighted below [1];

Using the formula: $\boldsymbol{K} = \mathbf{1}/\boldsymbol{N}\sum_{\boldsymbol{n}=\mathbf{1}}^{\boldsymbol{n}}(\mathbf{x}-\boldsymbol{\chi})^{4}\,\mathbf{(F)}/\,\partial^2 \qquad$ **(6)**

Where; N = total array of data; X = signal level
X = signal mean ; ∂ = standard deviation ($\mu 2$); F = probability density function

It is important to note that If the calculated value for K is greater than three (> 3); then the data is tending towards impulsiveness, which signifies presence of localized faults in the pump; such as cracked races, mangled bearings which in turn leads to large variation in kurtosis value and degradation of the a typical subsea pump [1].

The vibrational spectrum of a normal system is different from that obtained when defects starts to occur. Hence to model this trend, Kurtosis was adopted to identify transients within vibration signals and detect possibility of failure [21].

The outcome of condition monitoring based on Kurtosis is expected to deliver details on critical elements such as: process priority, cost effectiveness and likelihood of different failure mechanisms.

4. RESULTS AND DISCUSSION

In Table 2 below, Condition Monitoring analysis on an ESP (Electrical Submersible Pump) based on data obtained from [1] was done, to identify possible defects and predict future machinery degradation. X in Table 2 captures the vibration signal in In/Sec from the pump shaft component. M is computed as the average of the array of data. The data frequency is also captured as highlighted in the Table 2. Subsequently, the second order moment and fourth order moment is computed and the results used in computing the Kurtosis performance of the pump shaft.

Table 2: Kurtosis computation/ Result Analysis based on acquired data [1]

(M) Data Ave.	**(X) Array of data Vibration in In/Sec**	**Freq. (F)**	**(X-M)^2**	**F(X-M)2**	**(X-M)^4**	**F(X-M)^4**
10.86	17.5	1	44.02	44.02	1938.04	1938.04
	15	6	17.09	102.5	292.3	1753.8
	13.12	15	5.11	76.6	26.08	391.2
	11.66	13	0.63	8.19	0.399	5.18
	10.5	11	0.133	1.46	0.017	0.19
	9.54	8	1.755	14.04	3.08	24.64
	8.75	6	4.47	26.82	20.01	120.06
	8.07	4	7.77	31.08	60.5	242
	7.50	2	11.32	22.64	128.21	256.42
	7.00	1	14.93	14.93	223.1	223.1
	∑	n= 67		**342.28**		**4954.63**

$$M = 10.865$$

$$\sum F = 1 + 6 + 15 + 13 + 11 + 8 + 6 + 4 + 2 + 1 = 67$$

The second moment (μ_2) is calculated as: **∑F(X-M)** ^{2}**/ n** where n is the sum of frequency;
$\mu_2 = 342.283/67 = 5.108$
The fourth moment (μ_4) is calculated as: **∑ F(X-M)** ^{4}**/ n;**
$\mu_4 = 4954.63/ 67 = 73.94$
Kurtosis; $= \mu_{4/}\ \mu_2^2 = 73.94/ (5.108)^2$
$K_u = 2.83$

Since the above value is less than (≤3); it then follows that the array of data follows a normal distribution and the ESP is less impulsive. Hence no likely defect found on the pump. Also, computing the availability of the subsea pump indicates

$$Availability = \frac{2.83}{3} = 94.3\%$$

Hence, considering the 94.3% availability of the subsea pump based on the vibration analysis data of the pump shaft data, it is clear that the pump is operating at an optimum condition with fewer tendencies of high-level degradation or subsea pump failure.

4.1 90% Confidence Interval

For a normal kurtosis distribution, its 90% confidence interval must contain a zero; depicting a curve which transcends from a negative point through (0) to a positive point [1].

From the data given in Table 2, it follows that 90% confidence interval:

$(Ku-3) \pm 1.645\ (\sqrt{\{24/n\}})$
Which implies; $-0.166 \pm 1.645(\sqrt{24/67})$
$-0.166 \pm 1.645(0.598) = -1.515/\ 0.818$
Hence the 90% confidence interval for this distribution:
$-1.515 \rightarrow 0 \longrightarrow 0.818$

This implies that the degree of accuracy of the result is 90%.

4.2 Future Predictions Using Results

The results presented in Table 2, can assist in the planning of maintenance and given the current result, the subsea pump is still at its optimum performance. However, based on established standards for offshore equipment maintenance as highlighted in [5], there will be need to perform similar proactive condition monitoring test on the subsea pump shaft say in the next 3 – 4 years, to ascertain the degree of performance of the subsea pump and plan maintenance adequately.

It is also important to note that Kurtosis can be easily programmed into cloud-based condition monitoring systems, which is the future of condition monitoring in the Offshore/Subsea industry.

Generally, For Ku≤ 3; the GR (Gaussian Ratio) is estimated to be linear factor in the order of (3- Ku) which also signifies normalcy [22]. For Ku≥3; the GR (Gaussian Ratio) is estimated to be a nonlinear factor in the order of $(Ku-3)^{-1}$ which indicates need for intervention [22].

4.3 Identifying Failures and Remediation Steps

It is important to note that early condition monitoring allows for the detection of failures in systems and prepares engineers against accidental breakdown of equipment, which can slow down production with large cost implications to the company.

Major subsea systems like the ESP, pipelines and transportation system require a rigid monitoring apparatus, which identifies failures and contains management system database on remedial tactic.

Table 3 illustrates some subsea systems with its potential vibration failures and method of remediation.

Table 3: Subsea Pump Potential Failure and Remediation Steps

Subsea system	Potential failures	Remediation steps
ESP	Shaft vibration; caused by method of production which allows inadequate stiffening of long shafts	Adopting kurtosis for monitoring of vibration data of subsea pump shafts and programming the cloud based CM system that will be based on kurtosis to set-off alarm/warning signal when critical vibration limits are being approached for long shafts.
	Deviation in shaft concentricity by only 0.0025 Inches can also induce enough vibrations to shorten bearing lives from years to months.	Adopting kurtosis to future cloud based CM systems, to monitor possible deviation in subsea pump shaft concentricity, in order to ensure that the correct decisions are made to manage subsea pump shafts deviation issues.
Production Flow-lines	Corrosion, root intrusion, joint dislocation, tuberculation and ground settlement	Introducing strong signals into CM systems that can detect depletion in pipe thickness via vibration signals, detect dislocation of pipeline-riser systems on real-time basis and enable maintenance teams to react proactively to maintenance issues.
Subsea multiphase pump	Leakage of oil via worn out oil seals	Adopting kurtosis for monitoring the degradation of subsea multiphase pump seals and ensuring on-time replacement of worn-out seals.

4.4 Summary of Results and Discussion

It is important to note that the outcome of the condition monitoring based on Kurtosis indicated 94.3% availability of the subsea pump shaft, which implies that the subsea pump shaft is still at its optimal performance stage with fewer tendencies for degradation or possible failure. The subsea pump shaft is also a very critical element of the subsea pump and hence there is need for subsequent proactive monitoring between 3 – 4 years from the last vibration assessment of subsea pump shaft or better still with future cloud based CM systems, Kurtosis can be programmed into monitoring systems deployed on the case-study offshore field to enable a robust proactive condition monitoring of subsea pump shaft. The advantage of a proactive CM system based on a robust algorithm like Kurtosis is that the need for maintenance on the subsea pump will be identified on time and maintenance planned to reduce possible loss in production as a result of the malfunctioning of the subsea pump or the failure of the subsea pump.

5. CONCLUSION

This paper reviewed existing approaches for condition monitoring of mechanical equipment used in subsea production, with emphasis on subsea pumps. Subsea pumps are very essential equipment used for reservoir pressure boosting in the oil and gas industry to enhance production especially when the reservoir pressure begins to deplete towards the late life of a typical offshore field.

This study used Kurtosis algorithm to evaluate vibration data for the shaft of a subsea pump. The results of the study indicated an availability of 94.3% for the subsea pump based on the analysed data. This implies that the pump is still at optimal performance. The advantage of using a proactive condition monitoring strategy, based on Kurtosis was highlighted in the discussion section as this will enable maintenance as at when due, thereby preventing undue loss in production.

Key recommendations from this paper are as follows:

- Proactive Condition Monitoring (CM) is critically essential to manage the current and upcoming offshore oil and gas projects in order to ensure optimization of production by preventing sudden equipment failure.
- Kurtosis algorithm provides a sound probability function considering the tailedness of data distribution and its ability to examine the lowest odds of failure occurring.
- Kurtosis is recommended for implementation on current CM techniques that are Cloud based or Wireless CM techniques. This when implemented will improve the rigour in assessing subsea equipment condition real-time.

ACKNOWLEDGMENT

The authors hereby seize this medium to deeply appreciate Afe Babalola University for providing an enabling environment for conducting this research.

List of Abbreviations

CAPEX	Capital Expenditure
CM	Condition Monitoring
CPM	Condition Monitoring Performance
ESP	Electrical Submersible Pump
GR	Gaussian Ratio
HPU	Hydraulic Power Unit
HPHT	High Pressure High Temperature
MTBF	Mean Time Between Failure

MTBR	Mean Time Between Repair
RMS	Root Mean Square
TCI	Technical Condition Index
TPI	Third Party Interference
MMboe/d	Million barrel of oil equivalent per day

List of Symbols

Symbol	Description	Unit
X	Array of Vibration Data	In/Sec
μ_2	Second Moment	Dimensionless
μ_4	Fourth Moment	Dimensionless
Q	Volumetric flow rate across the pump	Kg/m3
Δp	Differential pressure Across the pump	Psi
P	Shaft power consumed by the pump	Hp
η	Pump Performance	%
∂	Standard deviation	Dimensionless
μ_3	Third central moment	Dimensionless
K_u	Kurtosis	Dimensionless

REFERENCES

[1] Crossley, M. L. (2000). *The Desk Reference of Statistical Quality Methods*, 2nd ed.: ASQ Quality Press.

[2] Westwood, D. (2017). Maintenance, Modification and Operations Market Forecast 2017 - 2021. [Online]. Available: http://www.douglas-westwood.com/report/oil-and-gas/world-offshore-maintenance-modifications-operations-market-forecast-2017-2021/

[3] Yong, B. & Qiang, B. (2012). *Subsea Engineering Handbook*, 1st ed.: Elsevier Inc.

[4] Randall, R.B. (2011). *Vibration-based Condition Monitoring*, 1st ed.: John Wiley & Sons Ltd.

[5] Eriksson, K., Falk K., Melboe, H. & Mjaavatten, E. (2007). Subsea Pumping Systems: Intervention Prediction and Condition Monitoring Techniques, in *Proceedings of Offshore Technology Conference*, 2007, OTC 18537, pp. 1-8.

[6] Bloch, H.P. & Budris, A.R (2014). *Pump User's Handbook: Life Extension*, 4th ed.: The Fairmont Press, Inc.

[7] Langli, G., Masdal, S.I., Nyhavn, F. & Carlsen, I.M. (2001). Ensuring operability and availability of complex deepwater subsea installations: A case study, in *Proceedings of Offshore Technology Conference*, 2001, OTC 13002, pp. 1-15.

[8] Bencomo, A. (2012) "Applications of condition monitoring for the subsea industry," M. Eng. Thesis, University of Stavanger, Norway.

[9] Neri, R. & Falk, K. (2006). Subsea architectures to facilitate increased recovery from reservoirs: Subsea processing, condition monitoring and process optimisation in a modern subsea control system, in *Proceedings of Subsea Controls and Data Acquisition*, 2006, pp. 141-149.

[10] Eriksson, K.G., Homstvedt, G., Melboe, H. & Gillespie, A. (2009). Predictive Condition Monitoring for subsea pumping systems, in *Proceedings of Offshore Technology Conference*, 2009, OTC 19872, pp. 1-23.

[11] Karassik, I.J., Messina, J.P., Cooper, P. & Heald, C. (1986). *Pump handbook*, 1st ed.: McGraw-Hill New York.

[12] Af Sätra, U., Christensen, R., Tanase, A., Koppervik, I. & Rokke, E., (2011). Proactive Maintenance in the Context of Integrated Operations Generation 2, *SPE Econ. Manag.*, vol. 3, no. 2, pp. 102–108.

[13] Nowlan F.S. & Heap, H.F. (1978). *Reliability-centered maintenance*, 1st ed.: Dolby Access Press.

[14] Davis, B.E., Kelly, C., Kierulf, K., Eriksson, K.G., Normann, T. & Homstvedt, G. (2009). BP king-deep multiphase boosting made possible, in *Proceedings of Offshore Technology Conference*, 2009, OTC 20146, pp. 1-12.

[15] Uhlmann, E., Laghmouchi, A., Hohwieler, E. & Geisert, C. (2015). Condition monitoring in the cloud, *Procedia CIRP*, vol. 38, pp. 53–57.

[16] Balanda, K.P. & MacGillivray, H.L. (1988). Kurtosis: a critical review, *Am. Stat.*, vol. 42, no. 2, pp. 111–119.

[17] Fiori, A.M. & Zenga, M. (2009). Karl Pearson and the origin of kurtosis, *Int. Stat. Rev.*, vol. 77, no. 1, pp. 40–50.

[18] Westfall, P.H. (2014). Kurtosis as peakedness, 1905--2014. RIP, *Am. Stat.*, vol. 68, no. 3, pp. 191–195.

[19] Joanes, D.N. & Gill, C.A. (1998). Comparing measures of sample skewness and kurtosis, *The Stat.*, vol. 47, no. 1, pp. 183–189.

[20] Nandi, A.K., Liu, C. & Wong, M.L.D. (2013). Intelligent Vibration Signal Processing for Condition Monitoring, *Surveillance*, vol. 7, pp. 29–30.

[21] Marwala, T. (2012). *Condition monitoring using computational intelligence methods: applications in mechanical and electrical systems*, 1st ed.: Springer-Verlag London.

[22] Lutes, L.D. & Sarkani, S. (2004). *Random vibrations: analysis of structural and mechanical systems*, 1st ed.: Butterworth-Heinemann.