

Article

# The Use of Acoustic Emission Elastic Waves for Diagnosing High Pressure Mud Pumps Used on Drilling Rigs

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**Abstract:** Although mud pumps are vital components of a drilling rig, their failures are frequent. The identification of technical condition of these high-pressure piston pumps is difficult. There are no reliable criteria for the assessment of mud pump condition. In this paper, faults of the pump valve module are identified by means of acoustic emission (AE) signals. The characteristics of these signals are extracted by wavelet packet signal processing. This method has been verified by experiments conducted on a NOV (National Oilwell Varco) -made triplex 14-P-220 mud pump (mounted in the drillship). The results show that the wavelet packet signal processing method can effectively extract the frequency band energy eigenvalues of the signals. Besides, some operational problems associated with high pressure piston mud pumps are presented. A non-invasive method for diagnosing the technical condition of such pumps is being developed at the Maritime University of Szczecin.

**Keywords:** drillship; mud pumps; valve damage; diagnosing; acoustic emission; condition monitoring

## 1. Introduction

The search for new gas and oil deposits in seas and oceans is carried out by specialized vessels equipped for drilling at great depths. On-board drilling equipment has to meet extremely strict and critical requirements. Drilling at great depths is feasible by latest generation ultra deepwater drillships. These authors are conducting research aimed to develop a non-invasive test method and construct a diagnostic system capable of identifying the condition of mud pumps on deepwater drillships.

There have been few attempts to use elastic waves to diagnose the condition of mud pumps. Most of the studies refers to pumps installed in land-based drilling rigs [1–3]. In the case of drillships, specific factors have to be taken into account in condition monitoring. For instance, the pumphouse, with its relatively small surface area and structural integrity, houses a number of independently working devices. Many traditional systems monitoring the work of devices installed on ships are based mainly on the control of vibration processes. However, they determine symptoms related to certain problems occurring in the entire area of machine foundation. It is difficult to identify with certainty the specific place of origin, even more so to identify the element itself that generates increased level of vibrations. In their other works, these authors propose to directly monitor processes that result in early wear or damage. Further, the source originating these processes can be identified. High frequency elastic waves allow us to separate other signals, coming from nearby devices. Due to the relatively high frequency of the received AE elastic wave, we can be sure that it comes from the ‘close’ surrounding of the measuring sensor. Like in typical phenomena related to elastic wave propagation, the waves from

other sources (farther from the sensor) will attenuate by themselves. Diagnostic methods using AE signals in shipboard conditions may significantly enhance diagnostic accuracy.

Major advantages of AE-based diagnostics include:

- Independence of the environment in which the measurement takes place;
- Higher sensitivity to the detection of damage (before an external symptom is visible), compared to traditional measurements (vibrations, pressures, temperature, etc.);
- Applicability for most machines, regardless of their technical condition;
- Ability to identify the AE signal source location in the tested object.

The drillship is a self-propelled vessel equipped with most advanced dynamic positioning (DP) systems (Figure 1). Its characteristic derrick and technologically advanced ancillary equipment are used in the drilling of wells in ocean floor rocks.



**Figure 1.** An ultra-deep water class drillship.

The present study took place on ultra deepwater class drillships, intended for drilling wells at depths to 3600 m and hole length of up to 12,000 m. Such vessels, equipped with the latest systems of dynamic positioning, are capable of keeping the vessel in place at different weather conditions (with waves up to 11 m and wind speed to 26 m per second). The ship's position is maintained by six azimuth propellers, with a power of 5500 kW each.

## 2. An Analysis of Drillship Mud Pump Failures

Geological drilling on land and in the seabed is a highly advanced technological operation. Exploration in quest of oil and gas deposits takes place in increasingly deeper waters, which is possible thanks to latest drilling technologies. The process of drilling a hole in the ocean floor requires the use of special drilling fluids, which are primarily intended for taking away rock cuttings from under the drill bit and conveying them onto the surface. Other important functions include securing the well.

Drilling fluids are pumped from an oil rig down to the well by high pressure mud pumps, the main element of the high-pressure drilling fluid system, shown in Figure 2. It is the most important technical

system on a drilling platform, often regarded as the ‘heart’ of the drilling process. Yet, there are no reliable diagnostic tools that would identify the technical condition of the pumps [4,5].

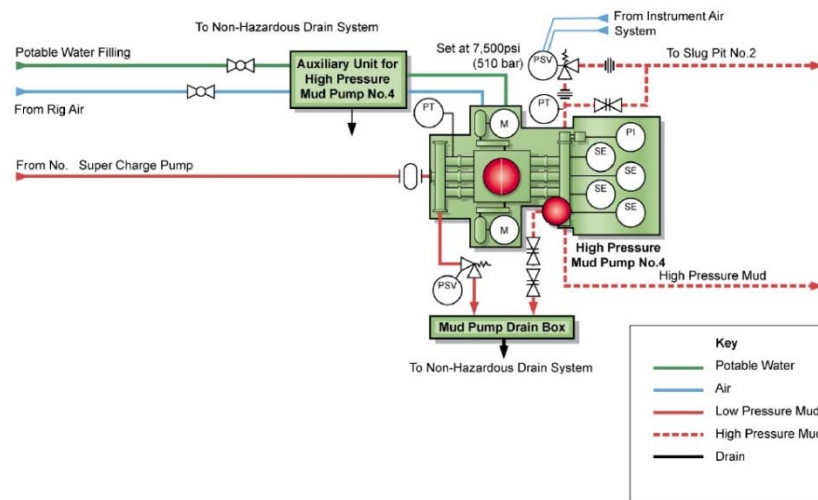


Figure 2. The system of a mud pump installed on a drillship [4].

Mud pumps installed on drillships require operational supervision of machines carried out continuously or periodically. Regardless of the adopted maintenance system, there are no tools to predict a failure. These authors are working on developing a method and designing a diagnostic system aimed to detect an early stage of changes/disturbances in the operation of a machine. The drilling process will not be affected if repairs are planned and performed as soon as practicable, without emergency shutdown of the running machine.

To confirm the importance of the issue, we have analysed the number of failures associated with mud pumps on one of the deep-water drilling rigs over the past three years. It has been shown that the most common type of failure referred to suction-discharge valves of the said pumps, displayed in Figure 3. Our studies have also shown that the periods between repairs differ significantly from those recommended by the manufacturer. These differences are due to the use of varied chemical composition of mud, quality of operation, and the adopted strategy of maintenance [6,7].

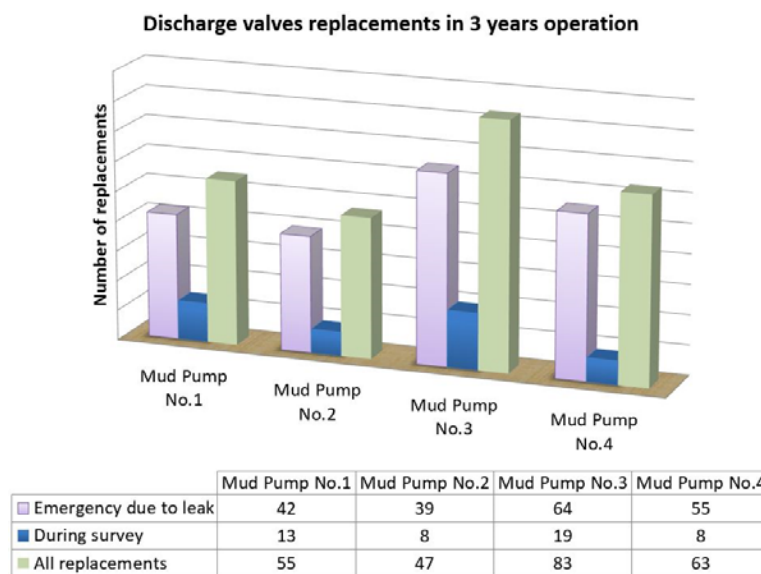
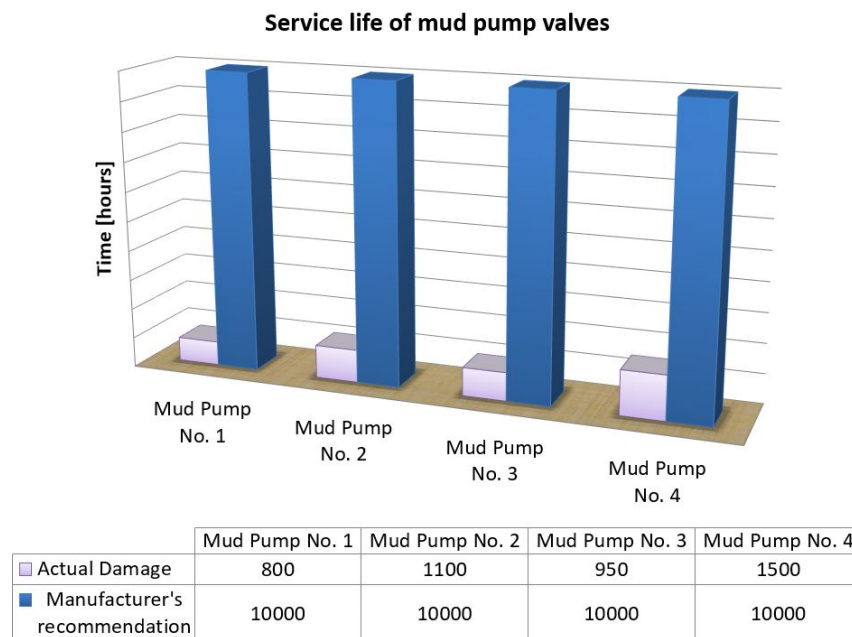


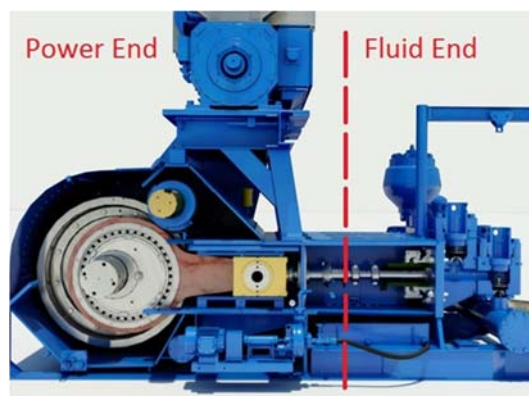
Figure 3. Analysis of the replacements of mud pump discharge valves on drillships [6,7].

The actual damage versus manufacturer's recommendations to the mud pumps is shown in Figure 4.



**Figure 4.** The service life analysis of mud pump valves on drillships [6,7].

The pump on which this study focused is a three-piston single-acting pump, referred to as the triplex pump. The drilling mud pump can be divided into two subunits, 'fluid end' and 'power end', as shown in Figure 5.



**Figure 5.** The mud pump made by NOV, divided into two most important components [7].

The fluid end is that part of the pump where pumping of liquids takes place, using such elements as pistons, cylinder liners and valves. Because drilling mud contains chemically aggressive substances, the life cycle of these elements is vitally reduced. That is the because of their earlier wear and unpredictable breakdowns.

The power end module is responsible for changing the rotary motion of the crankshaft into the reciprocating motion of the pistons. The crankshaft is driven by gear transmission connected to two AC/DC motors. In order to reduce vibration and pressure pulsations, pulsation dampeners are employed on the suction and delivery sides of the pump.

Offshore drilling companies Rowan Companies (RDC), Ensco (ESV), Seadrill (SDRL), Diamond Offshore (DO), Noble Corporation (NE), Transocean (RIG), and Ocean Rig (ORIG) rent out rigs to their customers and charge a day rate for this service. The day rate covers the daily rental fee charged to oil

drilling companies, but it only includes rig and labor costs—not the remaining costs related to the operation of the whole facility, such as equipment rent and chemicals. Figure 6 depicts the utilization and new contract day rate trends for the world’s ultra-deepwater drillship fleet [8,9]. For more cost-effective operation, and for personnel safety, it is important to seek methods of pump technical condition identification. The ideal solution would be to find diagnostic measures (descriptors) that would allow us to predict well in advance the technical condition of the vital elements of mud pumps.

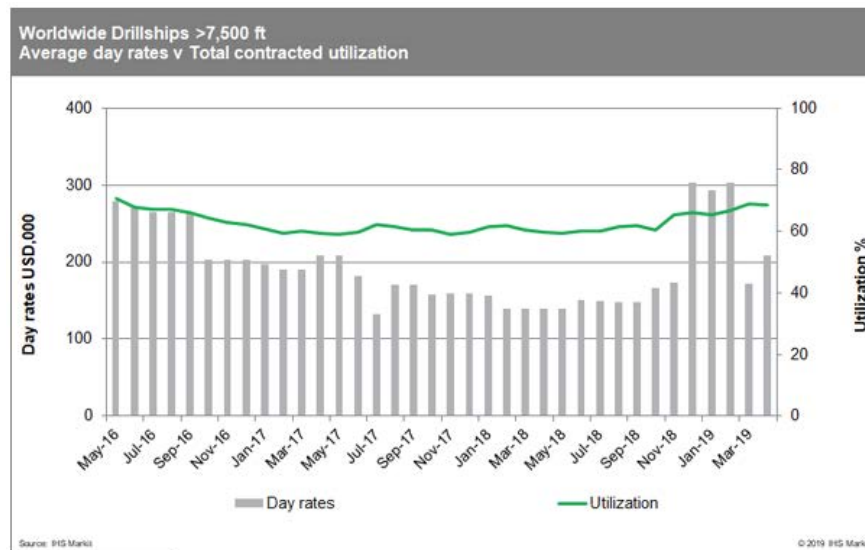


Figure 6. Offshore rig day rates [8,9].

The authors propose to use the propagation of acoustic emission elastic waves, or more specifically, the generation of certain characteristic frequencies associated with a particular kind of machine fault. In a classical case, in terms of physics, acoustic emission is a phenomenon of spontaneous generation of elastic waves by regrouping the internal structure of solids (seldom liquids) and physical systems. Elastic waves are also excited by sources affected by a physical process, such as flow of a medium, friction or local, dynamic change in the structure of the material (e.g., hitting of a valve head).

Failures related with mud pumps, or more precisely with leaking valves in the fluid end, might often be avoided through the implementation of the proper maintenance strategy [6].

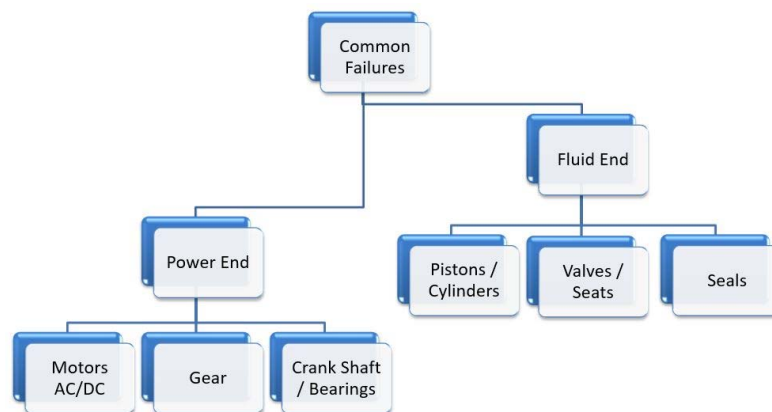
If a valve (see Figure 7) works more than 500 h at 100 cycles per minute, the spring will be subjected to 3,000,000 cycles. Given that, from a technical point of view, the spring should be replaced at each valve replacement. However, it is not the case for two seemingly mundane, yet existing in practice important reasons. In actual operations, one reason is minor: spare springs are not supplied with the valve as the recovery package (the valve and the spring are ordered as separate items). The other reason is the lack of users’ knowledge about the technical condition of the springs, thus the necessity of their replacement.

In operational practice, we should also consider other principles in order to maximize the life cycle of valves. First of all, when a valve is replaced, it is imperative that the valve seat should be replaced, too (and vice versa).

There are two sealing surfaces in the valve-seat interaction (see Figure 8). Where the function of one of them is impaired, the whole unit stops being tight (there is simultaneous erosive and abrasive impact of the working fluid on the working element).



**Figure 7.** A new valve head (left) and damaged seat and head of a mud pump valve (right) [4,6].



**Figure 8.** A fault tree for mud pumps.

One of the surfaces is an elastomer valve insert. Its primary function is to make the valve tight when it is closed. Valve inserts may be repeatedly replaced before the whole valve head-seat unit is replaced. The actual observations show that inexperienced personnel are often not aware of that. The other sealing area is the interface of bearing surfaces (metal-metal). Two metal surfaces touch each other when the valve rests in the seat. When a new valve head and seat are mounted, both surfaces are perfectly smooth. On a flawless surface, destructive forces are evenly distributed.

The valve modules are those parts that, when damaged, must be sent ashore for repair. Their most common defect is erosion-cavitation wear. An important part of the module is its cover and cover sealing. The cover is tightened or closed in different ways, depending on manufacturer's recommendations. The most important thing we should pay special attention to is hydraulic pressure of the press during the tightening of cover bolts. This pressure is very carefully specified by the manufacturer, and so is the module opening and closing procedure (while exchanging the valve, its seat or any other parts). Hasty and chaotic repair or failure to conform with the procedures may lead to grave consequences. It should be borne in mind that the pressure in the valve module reaches 515 bar. Leaks resulting from incorrect installation are caused by an insufficiently tightened valve cover. In this case, fastening the cover will not be a remedy: new seals will have to be mounted.

The gasket under the valve cover is also often neglected, while it should be checked during each valve cover removal.

### 3. Analysis of Typical Failures of Mud Pumps in the “Power End” and “Fluid End”

The most common problems related directly to mud pump breakdowns are shown in Figure 8. The fluid end subunit most often suffers from leaks. In the case of leaks related to the wear of piston-cylinder interface the symptom that indicates damage is the contamination of water cooling the cylinder liners (visible even if damage is minor), because working in the closed circuit the water returns to a cooling water tank. The problem relates to both discharge and suction valves. The wash-outs of

this kind are not visible. They can be detected only in advanced stages of damage when it is quite difficult to maintain a constant discharge pressure. In this case, it is necessary to stop the pump and replace the valves. The problem however is to identify which valve is damaged or which of them starts to malfunction. Experienced users attempt to assess the condition of these valve “by the ear”. These methods are, however, inaccurate and unreliable and involve comparing acoustic effects from the particular pump subunits at 15-min intervals.

The power end module, if properly maintained, mainly by controlling the lubricating oil quality and frequency of replacement is the component least subject to damage. Theoretically, it is possible the overload electric motors causing a fracture of the crankshaft, while in practice there are safeguards preventing the pump from reaching critical parameters. The gear transmission conveying the drive from electric motors to the pistons is liable to damage mostly caused by the malfunctioning of the lubricating system. The systems used are mostly based on monitoring of parameters, e.g., too low pressure on the oil pump or filter blockage. When such symptoms occur, an emergency stop of the pump takes place.

#### 4. Most Frequent External Factors Causing Mud Pumps Failures

External factors affecting the most vulnerable components such as valves include erosion, abrasion, corrosion, degradation caused by the chemical interaction of aggressive liquids and the temperature of the liquid pumped. Based on the visual check of worn out valve head-seat units we can find out which of the external factors affected its operational condition. An examined component may show that a few factors have had impact on its condition. As a rule, wear analysis leads to an observation that one type of wear was a primary cause of damage, the other are secondary consequences [4,6]. Table 1 classifies most frequent causes of mud pump component failures.

**Table 1.** Main causes of mud pump component failures [4].

Wear/Problem	Cause
1. Erosion	It is the most frequent cause of valve wear. If a metal or oblique elastomer part of a valve does not evenly stick to the seat, a gap will be formed. During pump operation, when the valve is in the closed position, the mud will be flowing out through the gap. Such leakage depends on the size of the gap, pumping pressure and temperature. The flowing liquid causes erosion that enlarges the gap by grooving it, a process in which gradually particles of the material are torn away from the valve. In the longer term, the gap will substantially grow on the valve. The valve degradation will continue until a point where the gap gets large enough to make the valve visibly leak. This phenomenon is usually caused by non-axial setting of the seat (or a new valve head and old seat). However, it may be a consequence of previous abrasive wear, occurring when solid particles from the mud (e.g., sand) got into areas of friction.
2. Abrasive wear	Abrasive wear is a direct characteristic associated with hard contaminants in the pumped liquid causing material loss in the surface layer through micro-cutting, scratching or ridging. Common abrasive materials are sands, quartz, iron filings, and chemical additives added to the drilling fluid. Valve components are heat treated to increase their abrasion resistance, but this does not eliminate the problem entirely. Impurities are disintegrated by the metal part of the valve creating sharp fragments that tend to settle in elastomeric inserts, initiating the formation of microfractures. In time the insert surface wears out much faster than the remaining part of the valve, resulting in its total damage excluding continued operation of the pump.
3. Corrosion	The phenomenon of instant chemical corrosion of pure metal occurs at the microscopic level. As the valve is affected by mud flowing under pressure, the valve and seat faces are washed out every time again to the pure metal. During the alternate cycles of rusting and washing out, microscopic cavities start to appear on the valve face surface. After a considerable period of pump running, these ‘micro-losses’ become more and more visible. At this stage, sharp edges associated with material degradation begin to destroy the whole valve surface. After continued operation the valve will be damaged so that only a small surface of the working unit will have contact. How long it takes to destroy a valve depends primarily on the type of drilling fluid, pump capacity and working pressure. Corrosive pitting occurs most frequently in places where the insert contacts the valve seat. In some cases, in order to extend the life and resistance to pitting corrosion of the elements under consideration, chrome plating or electroless nickel plating methods are used
4. Chemicals	Some chemicals and chemical compounds can cause gradual damage and degradation of the valve. As a result, the elastomer part of the valve is subject to crushing and gradually disintegrates. If during the dismantling of a valve its elastomer insert has a smell of a solvent or hydrocarbon, it is a sign of its degradation. In this case, the insert should be immediately replaced (even if the external signs of damage are not observed).
5. Temperature of pumped liquid	As the temperature of the pumped liquid rises, physical properties of elastomers decrease.
6. Type of the fluid base	Depending on the drilling fluid base liquid (usually oil or water), the components of mud pump sustain wear at a varying rate. This is closely related with other parameters listed as causes of damage to these components.

The causes of mud pump failures described in the table occur usually in combination with each other. For instance, quite often, the frequency of erosive wear depends on which base liquid is used and the associated temperature and chemicals used. Regardless of the cause of damage, from the operating point of it is essential to detect a fault early enough so that the drilling process will not be stopped. In other words, the perfect maintenance strategy would be “the condition forecasting/predicting”.

## 5. Application of Acoustic Emission for Mud Pump Diagnostics

It is difficult to locate the module where a fault (e.g., noticeable critical drop and fluctuations of pressure) has occurred in the mud pumping system. Classical vibration methods in this case prove useless for a number of reasons, e.g., the presence of large disturbances from other devices in the pump room [3,6]. At the same time, when a leak or other fault is detected, the whole drilling process has to be stopped. Consequently, the operational costs get considerably higher. Any malfunction or failure in the high-pressure system involves health and life risks of the operators.

These authors are developing a method of diagnosing mud pumps, i.e., their valves, as these are essential elements, whose failures or faults are hard to predict. The research is based on one of the most common types of pumps used on drillships (and land-based drilling rigs), triplex 14-P-220 mud pump made by NOV.

According to standard terminology of ASTM E1316-05 [10], acoustic emission (AE) is the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material, or the transient waves so generated. Acoustic emission is the recommended term for general use. Other terms that have been used in AE-related publications include stress wave emission, micro-seismic activity, and emission or acoustic emission with other qualifying modifiers. AE elastic wave is not confined to the audible domain, and the effective spectral range can extend to several or even tens of megahertz frequency range. The propagation of elastic waves in structural elements and in tested elements of mud pumps is subject to the phenomena of reflection and transformation of vibration modules at the phase boundaries of real objects. Therefore, analytical description of this phenomenon, the basis for measurements by AE method is very complex. It was assumed in the analyses that each of the propagation paths from the source to the point of observation is considered as a separate component in elastodynamic equations. In the AE source the function of amplitude changes in the stress field has a form of a unit/single peak, the sensor is placed in the pump body (housing of the valve unit, and the elastic wave propagates in a homogeneous medium. The basic equation describing the signal propagation path can have this form [11–19]:

$$G(x', t' - t; x) = \frac{1}{4\pi\rho v_p^2} \gamma_i \gamma_j \frac{1}{r} \delta(t' - t - r/v_p) - \frac{1}{4\pi\rho v_s^2} (\gamma_i \gamma_j - \delta_{ij}) \frac{1}{r} \delta(t' - t - r/v_s) \quad (1)$$

where  $G_{ij}(r, t' - t; r)$  denote Green's functions for dislocation in directions  $x'_i, y'_i, z'_i$  in point  $r'$  at instant  $t$ , when these dislocations are caused by a local disturbance of stress field in point  $r$  at instant  $t$ ,  $\rho$  refers to the density of the medium [ $\text{kg}/\text{m}^3$ ],  $v_p$  the dilatational wave speed,  $v_s$  the speed of shear wave,  $\gamma_i, \gamma_j$ —for  $i = 1, 2, 3, j = 1, 2, 3$ , source the receiver and receiver-source directional cosines,  $r$  the distance between AE source and sensor,  $\delta_{ij}$ , Cronecker delta, and  $\delta(x)$ , delta function equal to  $+\infty$  for  $x = 0$  and equal to 0 for the other values of  $x$ .

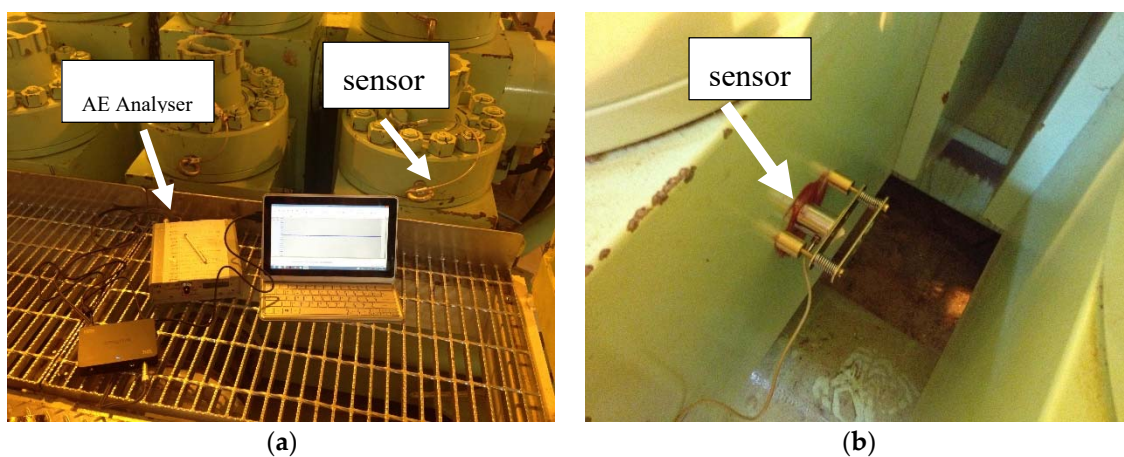
In real physical systems, such as mud pump system components, energy dissipation always occurs and therefore the amplitude–frequency characteristic functions do not tend to infinity in their resonant states. The effect of frequency change caused by the change in the attenuation rate is important. Wear and tear, and the tribological processes in friction nodes can therefore cause changes in the characteristic frequencies of the process itself. It can then provide relevant diagnostic information. Any damage to the tested facility causes a change in the AE elastic wave signal.



## 6. The Experiment and the Results

The results of tests performed by the authors refer to mud pumps 14-P-220 of triplex type, mounted on an ultra-deep-water drillship. A series of similar comparative tests for the same type of pumps were conducted during drilling at two different land-based drilling rigs. The sensor was pressed to the determined measurement point with constant force value using a special magnetic grip made by the authors (Figure 9). An AE acquisition system (made at the Maritime University of Szczecin) and an AE sensor with operating frequency range of 20–300 kHz are used. To reduce the scattering of elastic waves, silicon grease, acting as coupling fluid was applied between the sensor and the pump housing. The acoustic emission signal makes it possible to use non-linear methods of signal analysis in diagnostic inference. The following material characteristics are associated with these methods [12,14,15,18,19]:

- local deformation hysteresis and discrete ‘memory’ of the material,
- downward shift of the frequency resonance band, in proportion to the resonance amplitude, contrary to the classical case, where the shift is proportional to the squared amplitude,
- square dependence of the third harmonic amplitude, whereas using the classical theory of non-linearity this dependence should be raised to the third power,
- the level of attenuation depends on the amplitude,
- the phenomenon of ‘slow dynamics’, i.e., slow recovery of linear properties after the material was subjected to the impact leading to non-linearity.



**Figure 9.** (a) The measurement of the acoustic emission signal on the mud pump, (b) sensor location.

These effects are associated with large non-linearity, characterizing mainly gases and highly plastic materials (elastomers). In solid substances with crystalline structure, such as metals, the phenomenon of high non-linearity is often associated with degradation, the occurrence of cracks, creep, and other above-molecular defects typical of mezzo-scale damage [11,14–16,18,19]. In such cases, local elasticity is different for stretching and compression, and related non-linear effects lead to increased high frequencies of the harmonics. Similar phenomena occur in the case of components of the mud pump valve unit. In the valve unit the two impacts are combined, as it consists of the metal and elastomer parts. The non-linear and non-stationary processes are particularly evident here. Non-linear superposition of waves leads to the exchange of energy between them. This may result in the waves characterized by other frequencies. From the diagnostic point of view, this gives the possibility to use information on frequency changes to the identification and location of damage. The advantage of this method, distinguishing it from other methods of determination of physical and chemical properties of solids and liquids, results from the basic principle of acoustic emission measurement. The source of the recorded signal is the energy generated by the heterogeneity of the examined medium due to external stimulation or normal operation of the object. Based on practical observations, it is assumed that AE

signal generated by the pulse source has a form of attenuated sinusoids [10,16]. Electric voltage  $V_1(t)$ , expressed in volts, generated by AE converter during an AE event has this form [11]:

$$V_1(t) = A_m \exp(-\alpha_1 t) \sin(2\pi f_0 t) \quad (2)$$

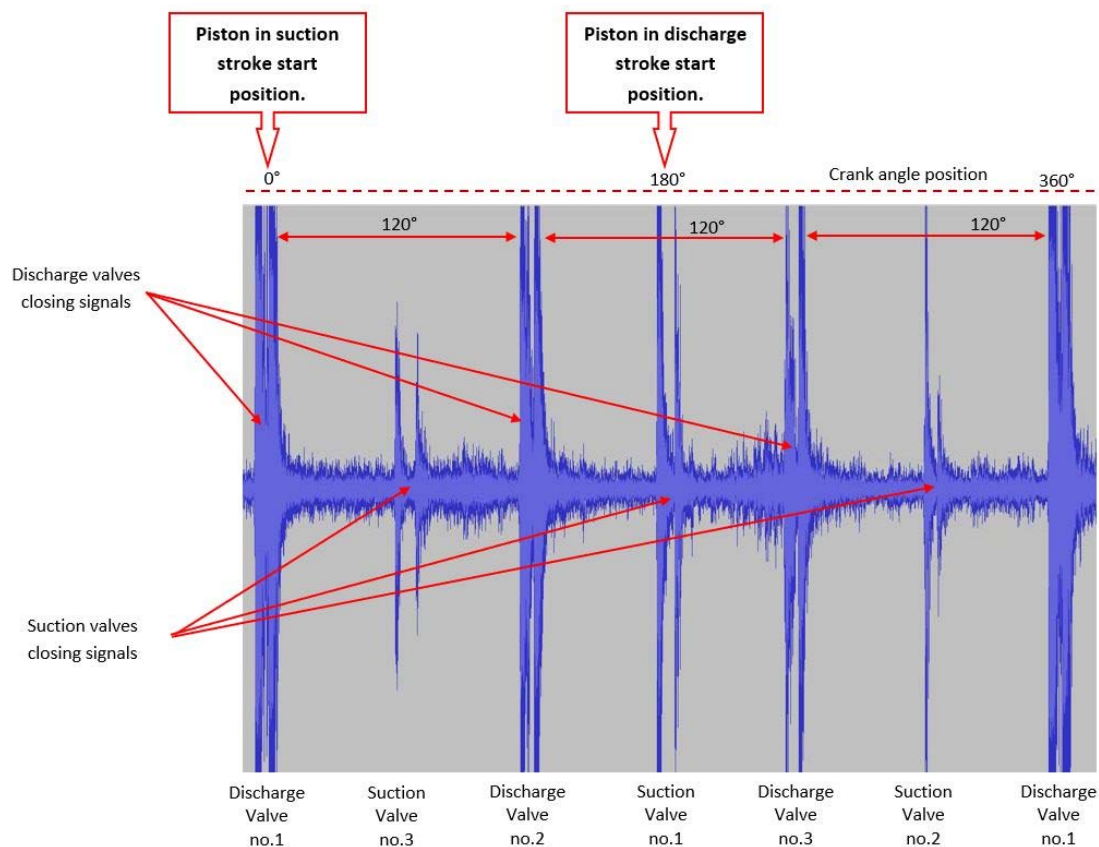
where  $A_m$ : peak value of voltage recorded in an AE event [V],  $f_0$ : frequency related to the maximum amplitude of the converter-medium system [Hz],  $t$ : time [s], and  $\alpha_1$ : attenuation coefficient for the examined converter-medium system [1/s].

The above formula can be modified to take into account the time of signal increase during AE event recording [10,16].

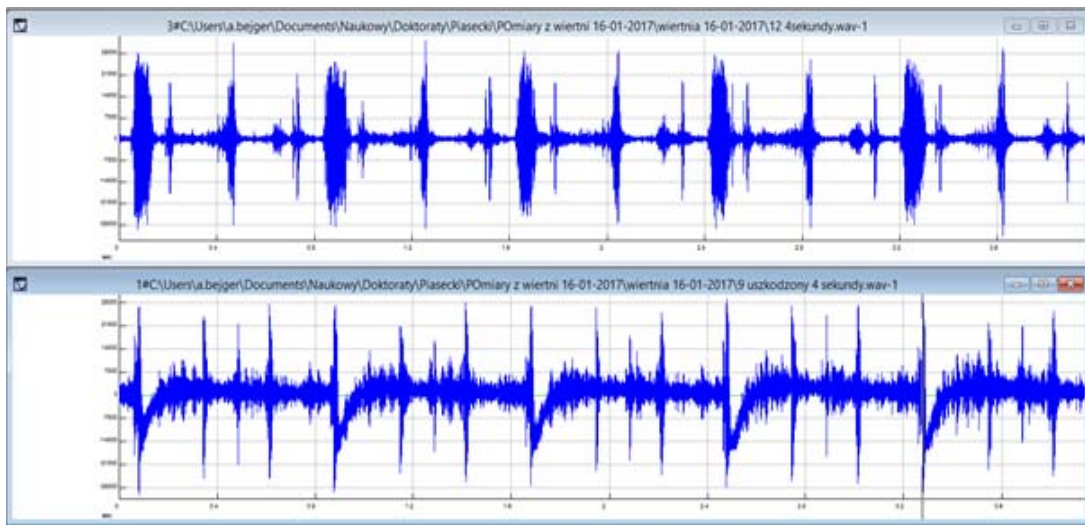
$$V_2(t) = A_1 [\exp(-\alpha_2 t) - \exp(-\beta t)] \sin(2\pi f_0 t) \quad 0 < \alpha_2 < \beta \quad (3)$$

where  $A_1$ ,  $\alpha_2$ ,  $\beta$  are parameters of signal shape during AE event.

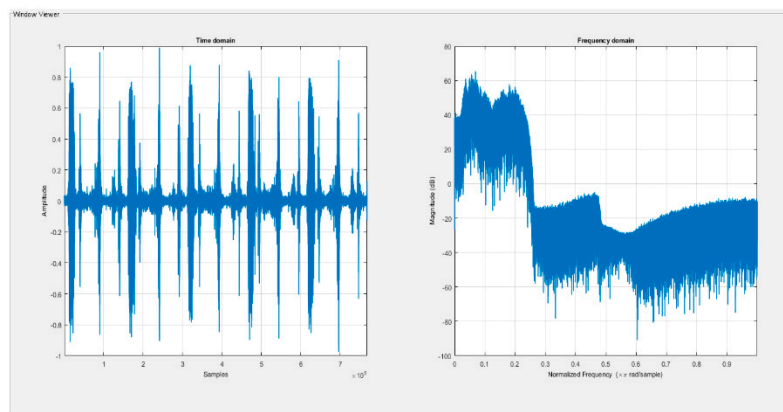
The terms (1) and (2) describe the burst type emission. Such signals are integrable and differentiable by analytical methods, which is used further in defining descriptors of acoustic emission. As mentioned earlier, the method uses phenomena occurring during the propagation of acoustic emission (AE) elastic waves. Once the measuring points were selected, the source signal of AE elastic waves was recorded (Figure 10). The signal illustrates successive stages of pump operation, including signals picked up from particular elements of the pump. Figures 11 and 12 present a comparative analysis of the signal from the correctly working, failure-free pump and (Figure 13) from a pump with an initial stage of elastomer insert damage. The signal is interesting from the operational and diagnostic perspective as the existing fault is not yet generating any external symptoms. This offers a possibility of “predicting” technical condition well in advance. The valve condition does not necessitate the suspension of the drilling process but scheduling a repair.



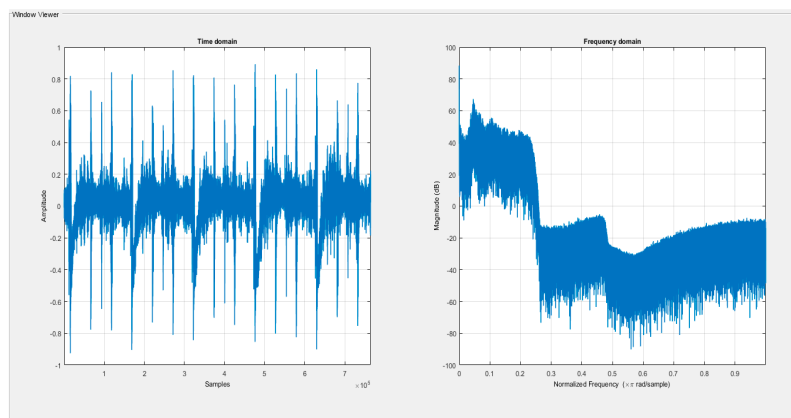
**Figure 10.** AE signal source from the running pump valves, with indicated stages of valve operation.



**Figure 11.** Changed signal generated by a valve head-seat unit failure. The comparison of the signal source of AE elastic waves from properly working valve unit of a mud pump (**up**) and early condition of the valve unit failure (**down**).

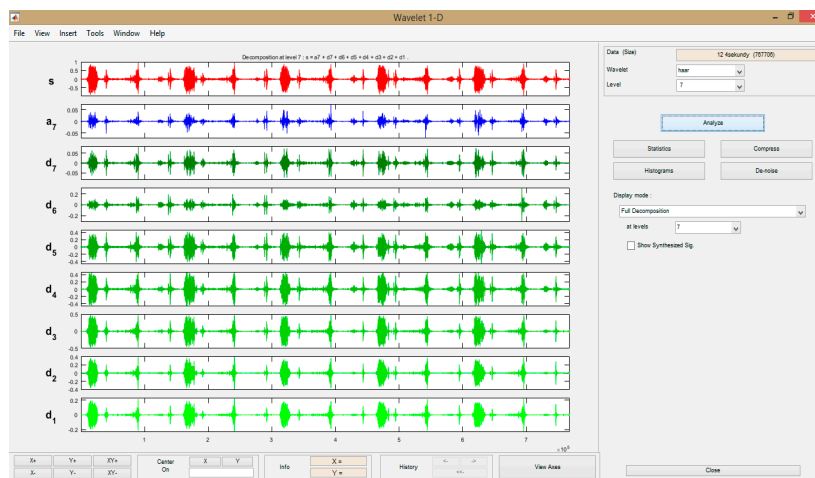


**Figure 12.** Analysis of the signal from the correctly working mud pump valve. The amplitude-time signal (**left**) and magnitude (dB) as a function of frequency (**right**).

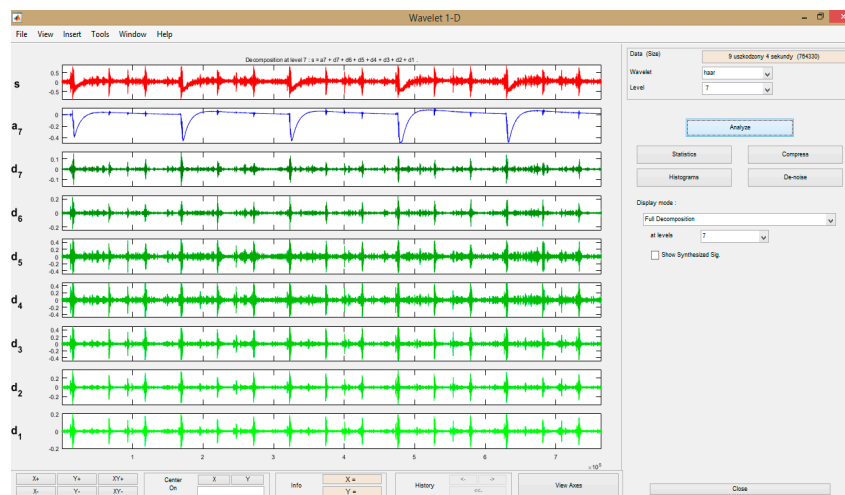


**Figure 13.** Analysis of the signal derived from working mud pump with a damaged valve (no external symptoms could be observed by persons responsible for the pump operation). The amplitude-time signal (**left**) and magnitude (dB) as a function of frequency (**right**).

Applying the previously described reasoning for a fault of a mud pump valve module system, we can find a symptom that indicates extending damage. It can be stated that in selected narrow bands, mainly low-frequency bands, the ordinary time-frequency function should be sensitive to even minor damage of valves' module. The most common forms of damage include abrasive wear, erosion, and cavitation wear. Therefore, in the analysis of feeding (pressing) the fluid to the valves, changes in the non-linear response of the system can be found. For better insight concerning the detected fault, the signals were subjected to wavelet decomposition (see Figures 14 and 15) using the Haar wavelet [19–24]. At the seventh level of signal decomposition ( $a_7$ ), there is a clearly visible effect from a defective valve. From the diagnostic point of view, the most essential is that the detected fault is small enough not to generate any external symptoms in pump operation. It is possible to detect damaged valve condition early, or to put it differently, the valve condition can be predicted.



**Figure 14.** The wavelet decomposition using the Haar function of a correctly working valve unit.



**Figure 15.** The wavelet decomposition using the Haar function for early detected fault of the valve unit.

The decomposition method consists in decomposing the signal into a number of functions (levels) with decreasing frequencies in such a manner that each level of decomposition contains a high frequency detail and approximation formed after taking away high frequency details from the signal. After decomposition, for each time series a graph was obtained. Each of the details represented a signal component of different frequency: higher numeral of the detail corresponded to a lower frequency. In Figures 14 and 15,  $a_7$  denotes final approximation, while  $d_1$  to  $d_7$  are high frequency components of the signal.

Frequency components of the signal obtained from the decomposition of the series  $x(t)$  are calculated by using the reverse discrete wavelet transformation of series  $D_{j,k}$  and wavelet transformation coefficients  $S_{j,k}$ , and are written as follows:

$$x_j(t) = DWTT^{-1}[D_{j,k}S_{j,k}] \text{ for } t = 0, 1, \dots, N-1 \quad (4)$$

where  $N = 2^p$  ( $N$ —number of data,  $p$ —number of frequency components);  $j = -p, -p+1, \dots, -1$  index of scale;  $k = 0, 1, \dots, 2^j N - 1$  index of displacement.

In addition to the AE analyser designed at the Maritime University of Szczecin, we used a professional portable measurement acoustic emission system, Pocket AE2 from MISTRAS (Physical Acoustics Corporation)—Figure 16.



Figure 16. Portable measurement system Pocket AE2 from MISTRAS.

Figure 17a shows frequencies characteristic of working mud pump valves. The analysis allows us to observe changes of power as a function of frequency (during the drilling process). Energy amplitudes of the acoustic emission are presented in Figure 17b.

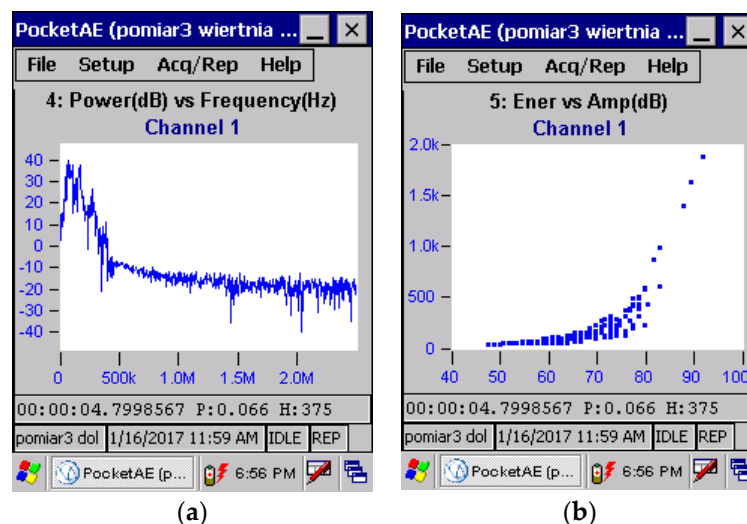
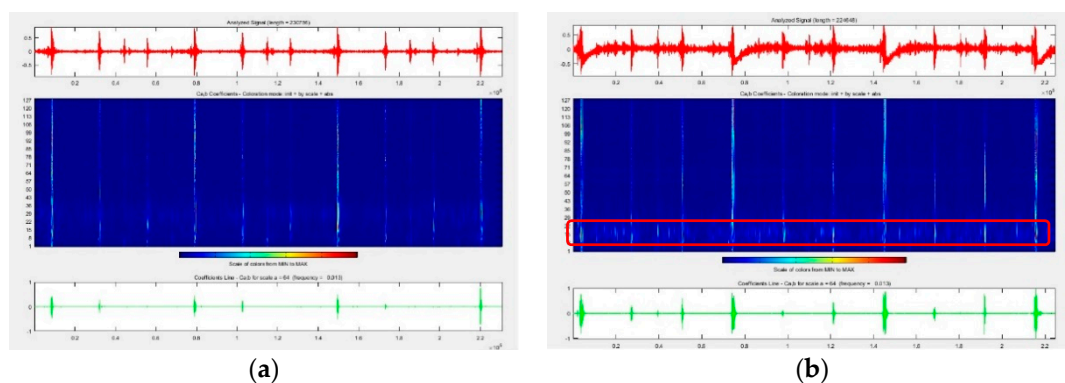


Figure 17. Analysis of AE signal power as a function of frequency (a) and energy amplitude of a signal (b) from a correctly working pump valve.

In order to observe the frequency variations for valve failure, the time signal was mapped onto a two-dimensional plane, determined by the time-frequency coordinates. In the present case, we exploited the continuous wavelet transform using the Morlet wavelet [24–27] described by the formula:

$$\psi(t) = Ce^{-x^2/2} \cos(5x) \quad (5)$$

The results of the conversion are presented in Figure 18, where the energy component of the signal emitted by the failure is visible in the form of wavelet coefficients (functions of scale and location), the values of which are extended in time, distributed on the time-scale plane, and their frequency has been reduced. The presented method allows for the observation of changes in the symptom we are looking for. Figure 18 shows the wavelet decomposition of an acoustic emission signal emitted by a new valve and a leaking valve.



**Figure 18.** Wavelet decomposition of the acoustic emission signal emitted by a new valve (a) and a valve with a leak (b).

In the wavelet decomposition, the signal from a damaged valve is visibly affected by low frequency components.

## 7. Conclusions

The article addresses common problems associated with failures of mud pumps installed on board the drillship Deep-Ship and the related research aiming at developing a method using acoustic emission elastic wave signals for diagnosing the condition of mud pump valves. The authors have analysed external factors that considerably affect the work of elements relevant to the drilling process, or putting it differently, the transition of a device from up state to down state. Some results are presented of the research seeking a reliable method for the identification of the technical condition of mud pumps. From the diagnostic point of view, the development of a condition monitoring method that would enable predicting the state of individual elements of the equipment under consideration before the commencement of drilling is extremely important. Currently, these authors carry out research related to mud pumps used on drillships and in land-based drilling installations. It seems that the acoustic emission signal is a good tool to be used for the identification of their technical condition.

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