

Listening to your pump: Mud Pump Diagnosis and Optimization Using Audio Data

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Abstract

The complexity of today's drilling projects, especially the need for sufficient pressure and flow rate for wellbore cleaning, challenge mud pumps manufacturers. Their efforts focus on the improvement of pump running time and efficient maintenance management to reduce or eliminate non-productive time and HSE risks. Drilling rigs rely on mud pumps to efficiently circulate the mud, and synchronized pumps are employed to minimize mud pulsation effects. The mud circulation system is of major interest during the drilling operation with 7% of the personnel time being spent on mud pumps and 26% on monitoring from the total time spent in the mud area.

Various methods and tools aid in the monitoring of rig components. Visual methods, together with selective data acquisition help people involved in the drilling process to make educated choices for the benefit of the equipment. Out of the multiple methods, acoustic data acquisition, monitoring, and interpretation does not require complex systems, and data interpretation can continuously be improved.

This paper presents some achievements on pump diagnosis using acoustic data interpretation and some future application, that can improve the pump maintenance management as well as a novel concept to synchronize pumps. Noise detection technologies will be described and linked to mud pump's working condition. Two experiments will be methodically explained in order to outline what could be a novel, real-time method to detect and address problems in time.

Introduction

Pumps are used extensively in the oil and gas industry to pump drilling fluid, in downhole applications during drilling, as well as multiphase fluid transportation and processing facilities. This paper focuses on the surface utilization of pumps in the circulation system.

Reciprocating positive displacement pumps are a key element of a drilling rig's circulation system. Reciprocating pumps, unlike hydrodynamic pumps, are hydrostatic in nature. These pumps use fluid pressure to transmit power. Conventionally, two duplex pumps would suffice for the circulating needs of a drilling rig, but with complex well designs and increased pumping needs, triplex pumps came into use. While duplex pumps are double acting, triplex pumps

are single acting. Triplex pumps are cheaper and more compact. So conventionally, two pumps would work at shallow depth for high flow rates and only one would be used for the deeper sections. Modern drilling rigs on the other hand have four pumps, three working in parallel while one is on standby (Bejger and Piasecki, 2013). In some cases, the standby pump is actually used as a riser booster pump, like in offshore drilling, to aid movement of cuttings in the annulus (Penwell, 2001).

The ease of conversion and proven offshore utilization has promoted the use of 7,500 psi mud pump systems in onshore drilling. The biggest advantage lies in adding pump flexibility in the drilling system. Moreover, greater power yields greater rewards. In 2014, with 46 fewer rigs, the drilling industry ended up drilling 12% more (45 million feet) (Spears & Associates, Inc, 2014). Even though increased pumping rates do not directly correlate to higher efficiencies, it is often seen as an alternative by contractors. Mike Simpson, Director of Operations Technology at Santa Fe International stated that "combining greater pump capacity with upgrades in other systems brings the best out of the drilling system". Over horse-powering of pumps by the contractors to increase rate of penetration and efficiency is not uncommon (Penwell, 2001). This often results in greater wear of these pumps. In the long run, this wear can lead to malfunctions and unplanned pump shutdowns. It is vital to monitor these pumps as losing a pump can lead to hours of non-productive time and thousands of dollars lost. Expenditure for oil and gas infrastructure cost \$12.1 billion in 2016, making this industry critically dependent on efficiently running equipment (Freedonia, 2016).

The safety of operating a mud pump cannot be looked at like for any other equipment. The overall operational safety of a well depends on the continuous flow of drilling fluid. To avoid sudden failure of mud pumps, early signs of wear have to be recognized and diagnosed. Five of the most common maintenance problems include improper sizing of equipment, lubrication contamination, seal failure, improper elastomer material selection and ineffective baseplate design for the pump (EP, 2016). These can cause pump inlet restriction, leakages, high temperature and cavitation issues. While basic maintenance techniques include preventive and proactive methods, condition based monitoring system is one area that is

being explored with new innovations. This is derived from other disciplines like marine, process, and gas transportation industry (Nystad, 2008). Vibration and sound sensors are useful tools that have been previously utilized in automobile industry to detect knocking during bad ignition. Temperature sensors are also proving to be a vital indicator of the pumps health as damaged bearings and unwanted vibrations can cause friction and temperature increase in the system (Berge et al., 2014).

The most thorough maintenance techniques will require extensive understanding of the mud pump condition in real time to target maintenance schedules. This involves placement of sensors on pumps. Since dynamic monitoring is expensive, only the critical pumps are monitored this way. The remainder ones can be monitored using portable monitoring devices and handheld tools (Emerson, 2015). This paper presents an acoustic data acquisition concept that does not require a complex hardware to run parallelly. This can greatly help in finding early signs of wear in the mud pumps.

Condition Monitoring Methods

Monitoring pumps is a fairly difficult enterprise. Not only because of the variety and complexity of pumps being used but also because of the skilled personnel required for this task. While some of the most basic monitoring techniques include visual or audio detection, these techniques also require years of experience to perfect (Kyllingstad et al., 2011). Moreover, there is a growing concern for the arising experience gap due to new professionals entering the industry. These techniques require proximity inspection in mud pump rooms that also house up to eight centrifugal pumps for fluid mixing. The noise levels make detection of a malfunction difficult. Furthermore, dealing with pressures up to 7500 psi can represent a life risk.

Conventionally, operators employ equipment monitoring methods periodically or continuously, depending on the size, costs, and level of risk associated with the monitored machinery (Mitchell, 1993). With the increase in portable computational power at lower prices and the better quality of sensing technologies and methods, acquiring and transmitting data at the drilling site becomes easier to justify and implement (e.g. downhole drilling data being analyzed in real-time in remote service centers, pressure and temperature of surface production facilities sent to mobile devices, etc.). For observing rotating machinery, technologies used include motor current monitoring, lubricant analysis, thermography, dynamic pressures recording, usage of operating state sensors (e.g. speed), vibration and sound sensing, the latter being a more novel method discussed in this paper.

According to John S. Mitchel (1993) and Brown and Jensen (1990), the main objectives of condition monitoring and predictive maintenance programs (or PMP) are to:

- Maximize machinery availability by reducing unexpected, unplanned outages;
- Minimize hazards to personnel and the release of toxic and/or flammable material to the environment;

- Minimize maintenance costs;
- Verify effectiveness of repairs;
- Assuring that the root causes of chronic, repetitive problems are located and corrected;
- Improve awareness of machinery condition.

Acoustic Measurements

Sound is a vibration that propagates as an audible mechanical wave of pressure and displacement. Ultrasounds and infrasounds find themselves outside of the hearable (or audible) spectrum of 20 Hz to 20 kHz. Standard properties of sound waves can easily be sensed by generic microphones. These are frequency, amplitude, sound pressure, speed, and direction (Rossing, 2015). Microphones measuring broadband sound pressure levels from various sources transform variations of pressure into electrical signals. The sound pressure is usually expressed in decibels for a reference level of 20 milipascal (corresponding to the minimum sensitivity of a healthy human ear) (Johnson, 1994). Today's most common microphones for monitoring purposes are condenser microphones operating on a capacitive design. These are selected according to their application, the type of sound field (e.g. open air, closed spaces, etc.), frequency response and the required sensitivity. In post-processing, microphone signals are correlated with the sound source and displayed in a sound pressure-frequency spectrum obtained via Fast Fourier Transformations, providing a deeper understanding of the signal itself (Ichim and Teodoriu, 2015).

Various authors have reported successes with acoustic monitoring of rotating equipment. Because microphones have a wide bandwidth, the acquired sound signal carries more information than vibration sensors or accelerometers (Benko et al., 2005). A popular use of this measurement is to monitor car engines' condition. Modern cars rely on simple microphones to detect the so call engine knocking, adjusting the ignition parameters. Normally one or two microphones are mounted on the engine body, being designed to respond to a very specific frequency range. Oikawa et al. (1997) presented a complex audio monitoring system for a thermal power plant, which efficiently detects unusual sounds coming from different components and informs the users. According to Praveenkumar et al. (2017), sound signal has been used for fault diagnosis of a rotating bearing element and its analysis, together with vibration analysis, adds value to the emerging signal processing methods. Cudina (2003) has shown that in centrifugal pumps, the recorded audible spectrum can be used to detect incipient cavitation and its development, which is known as detrimental to the pump performance. Moreover, through the use of microphones, Nagaya and Murase (2011) detected and described cavitation in pipes through the use of directional microphones. Ichim and Teodoriu (2014) proved the potential of acoustic measurements for condition monitoring of a piston pump through correlating the check valves behavior with the piston axial movement in time.

Case Studies

In what follows, the application of acoustic measurements on a reciprocating and a centrifugal pump is presented. First, a proof of concept is shown by correlating acoustic measurements with a secondary measurement method, and secondly, we show how changes in the equipment working condition influence the acquired acoustic signal.

Reciprocating Drilling Fluids Pump

An experimental setup presented by Ichim and Teodoriu, (2015) shows the potential applicability acoustic monitoring of a reciprocating pump's condition. A commercial Digital Audio Workstation (DAW) software was used for processing the acoustic signal received by pressure field microphones placed on the ball check valve covers of a reciprocating mud pump. The software offers a live view of the acquired signal and has extended post-processing options. Four sample sets of the mud pump working condition were recorded and one random set of samples was taken into consideration for interpreting the data, because of their similar amplitudes and frequencies.

These samples made the object of the following interpretation. As noticed, the amplitude of the upper front valve waveform is generally higher than the right low valve amplitude throughout the recorded time windows (see **Figure 1**). This is the result of the upper front valve being situated on top of the cylinder and closer to the pressure dampener, both yielding higher sound pressures that are picked up by the pick-up microphone situated on the valve cover

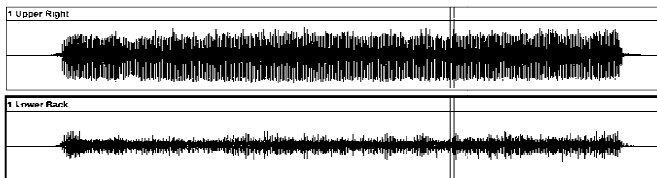


Figure 1 – Recorded Waveform of Upper (Top) and Lower (Bottom) Valve (after Ichim and Teodoriu, 2015)

In order to interpret the data, the recorded samples are analyzed in a Fast Fourier Transform spectrometer before and after noise filtration and sound quality enhancement. Because no standard condition of the working machine was obtainable, there is no comparison with the new state of the mud pump. However, by using the recorded samples (see **Figure 11**), the time for a complete stroke (the delay between one valve opening and closing) is calculated as 218 ms. This is also the time for a complete stroke and delivers the pump's number of strokes per minute (spm). The obtained value of 275 spm deviates from the manufacturer given one by -15. Since the pump was used, this could have been caused by pump wear, light damage, or by error of data interpretation. The result was verified with the help of a stroboscope, which measured 280 spm, so the method's accuracy is reliable (Ichim and Teodoriu, 2015).

To get a better understanding of the recorded waveforms from Figure 1, they were viewed in a spectrometer which plots

sound pressure amplitude (dB) versus frequency (Hz) at each point in time (every 36 ms in this case), see **Figure 2**. The raw data (Figure 2 – top) displays a high amount of unwanted high frequencies (8192 to 16384 Hz), which mainly come from the plunger/rod movement and pressure dampener.

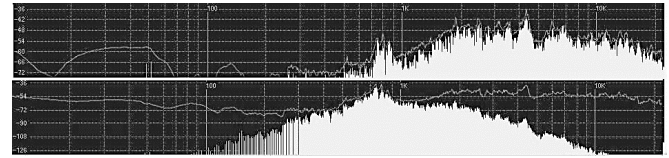


Figure 2 - TFFT dynamic viewing of recorded samples before (top) and after (bottom) filtering (after Ichim and Teodoriu, 2015)

Filtering unwanted signals is necessary for an accurate data interpretation. By using band pass filters, high frequencies stay outside the interpretation spectrum. After filtering high frequency signals, the waveform changes its shape and shows the up and down movement of the pump valves metal balls (Figure 2 - bottom) which can also be heard. Had a pump standard condition been available, the comparison between the two states (new – current) would have been possible and would show the differences between the two systems. In this manner, delivery of a conclusion about the valve status would be possible (Ichim and Teodoriu, 2015).

The proposed setup can, of course, be extended to other parts of the mud pump to determine additional characteristics of the mud pump working condition or.

Centrifugal Transfer Pump

The centrifugal pump monitored in this approach is part of a testing stand able to induce cavitation by adding air to a closed flow loop. The experimental setup was used to determine vibration changes with additional air entering the system, which also induces cavitation (Minescu et al., 2015). Later, a high-fidelity field microphone paired with the DAW were used to record the sound of the pumping system with and without air, in order to analyze the system's characteristic noise (see **Figure 3**). The aim of this was to observe ability of the sound monitoring technique to identify the status of the pump. Since the pump was designed to operate with liquid only, any undesired air entering the system could lead to pump malfunction. Air was added to the system while pump vibrations and sound measurements were taken. We decided to use one single microphone, “listen” to the pump overall sound, and draw conclusions solely on the acquired signal, similar to what a pumper would conventionally do in the field. However, as we use a computer to replace the “pumper”, we have to perform a series of tests and data processing in order to give the computer a comparison baseline and have a database of acquired signals correlated with air and liquid flow rates.

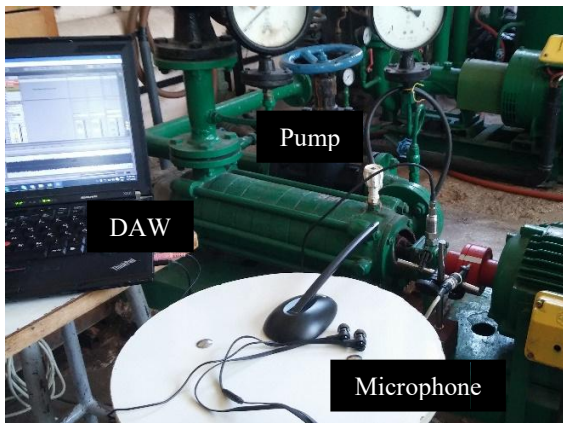


Figure 3 - Centrifugal Pump and Sound Recording System (Stan et al, 2018)

Figure 4 shows the recorded waveforms for the centrifugal pump. Although no major differences can be observed, by viewing the time-based amplitude-frequency spectrum of these waveforms, some features are observed.

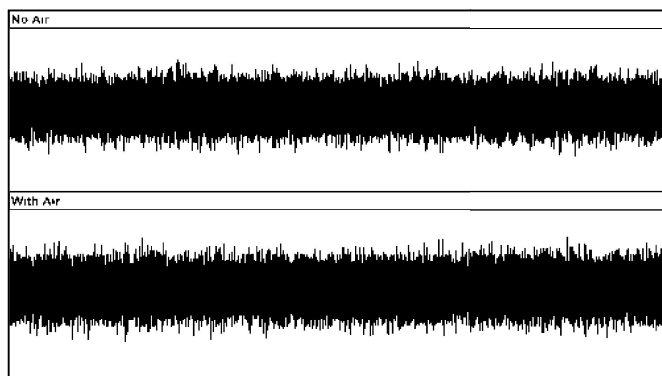


Figure 4- Centrifugal Pump Recorded Waveforms without (top) and with (bottom) Air

Figure 5 presents the full frequency domain of the recorded centrifugal pump audio sample at two minutes after the pumping system was turned on. The white line represents the acquired signal without air in the system, whereas the darkened gray surface represents the signal recorded when air enters the system.

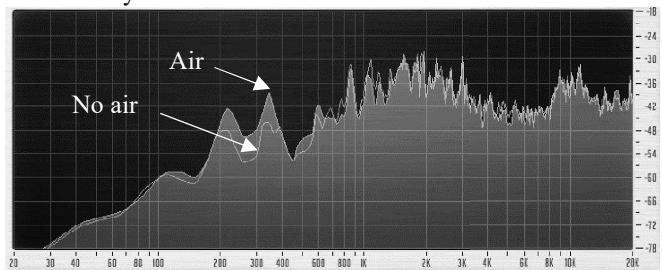


Figure 5 – Frequency Spectrum of the Centrifugal Pump (after Stan et al. 2018)

Figures 6 and 7 present a zoomed-in view on zones of the spectrum where we observe differences between the two

working conditions. At frequencies between 150 Hz to 1.2 kHz, different amplitudes are present when air enters the pumping system, as also observed below (2 to 4 dB at 176 to 420 Hz and 2.2 to 2.4 kHz). Figure 7 displays the spectrums for the middle frequencies, where again, some disparities between the two working conditions are present. As seen in Figure 5, above 9 kHz the two acquired signals are similar.

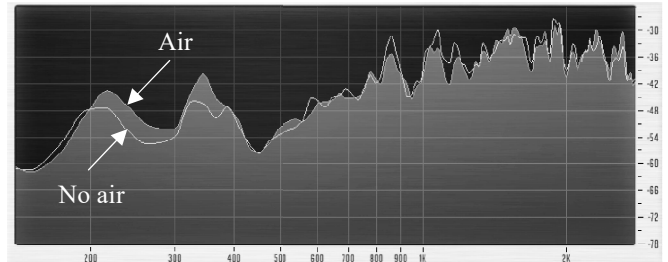


Figure 6 – Spectrum from 150 Hz to 2500 Hz

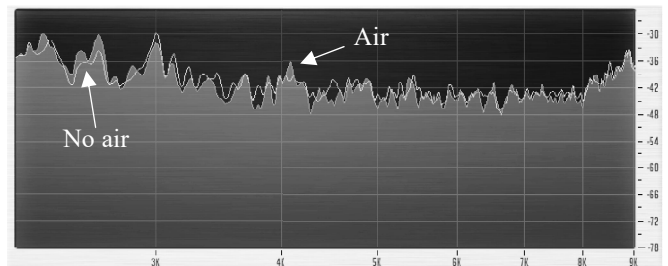


Figure 7- Spectrum from 2.5 kHz to 9 kHz

Analyzing the amplitude-frequency behavior with time can provide valuable insight into the equipment condition. Moreover, alarms can be set and started when the live signal deflects by a certain percentage (considered harmful to the equipment condition), so that the operator can take a decision regarding further investigation and necessary steps to keep the pump online.

Data Transfer

As shown above, the computerized recognition of possible events requires the establishment of references or samples that can be used by the computer to take a decision. There are several methods to do so, but we have considered for our experiments the following concepts:

- Generate a curve or audio recording for non altered given load curve for the pump
- Use the continuous monitoring and compare current status with previous status
- Push data to a high-performance computing unit and perform real time comparison using prerecorded data and data analytics.

The later concept will require the highest investment, but would allow the monitoring of multiple systems using a common database for the reference samples.

Figure 8 presents an idealized concept of the data acquisition and transfer system, which would offer live insights into the pump operating conditions.

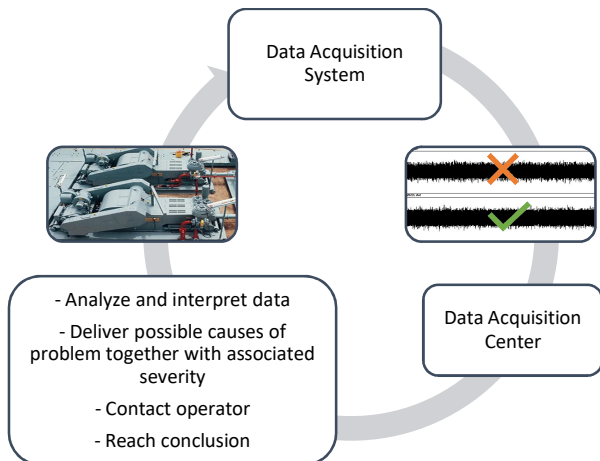


Figure 8 - Data Acquisition and Interpretation Concept

As shown in **Figure 8**, the signal is recorded locally by a Data Acquisition System (DAS) consisting of the microphones placed in the pump vicinity. The DAS can compare the recorded signal with a given signal, representing the pump optimal operating conditions, if an alarm limit is reached, the DAS sends a notice together with the data to a center, where it can be analyzed, and next steps can be planned. This ensures a timely diagnosis of potential severe conditions, which can later lead to pump malfunction, non-productive time, higher costs, and potential risks and hazards.

A Modern View of Pump Synchronization

Pump pulsation becomes an issue in applications which use drilling fluid for data transmission, such as mud pulse telemetry. Modern alternative current (AC) driven pumps, use computer controlled concepts to synchronize the crankshafts of the pumps, so that when using, for example, three triplex pumps, the pressure peaks occurs every 40 degrees instead of 120 degrees per each pump. **Figure 9** shows a comparison between synchronized and non-synchronized pumps. For comparison, **Figure 10** presents a typical triplex pump flow discharge, where the highest peaks are at 120 degrees of crankshaft rotation.

As shown in the first case study (Ichim and Teodoriu, 2015), the so-called mechanical sound of the mud pump valve can be extracted from the total noise of the pump through sound visualization and post-processing, thus offering a new idea for pump synchronization. The moment of pump valve opening/closing will trigger an event in the recorded waveform (see **Figure 11**, a zoomed-in view of Figure 1), which can also be viewed on the Fourier transformation of the sound wave (Figure 2). In more detail, Figure 11 shows acoustic events triggered by the bottom and top valve opening/closing and the delay between them, used for the calculation shown in the first case study. These events can be used to first diagnose the valve and its status (i.e. malfunctioning), but also could serve as a base for pump synchronization, particularly when a compressible fluid such

as foam mud is pumped. The main difference to the crankshaft synchronization concept lies in the fact that the valve movement is typically slightly delayed from the piston motion, hence they will close and open slightly after the piston reaches the two extreme positions.

As shown above, sound analysis can also detect the change of the flow through the pump manifold. Therefore, the presence of microphones at the pump valve body can recognize any change in fluid flow that could be the first stage of pump malfunction. Mainly air entrance into the pump will be recognized through the change of frequency, whereas cavitation can be recognized through knocking type of sounds. Since most of the triplex pumps will require a centrifugal pump for inlet pressure boost, the placement of a microphone on the centrifugal pump will help early detection of air suction, that could affect the triplex pump functionality and integrity.

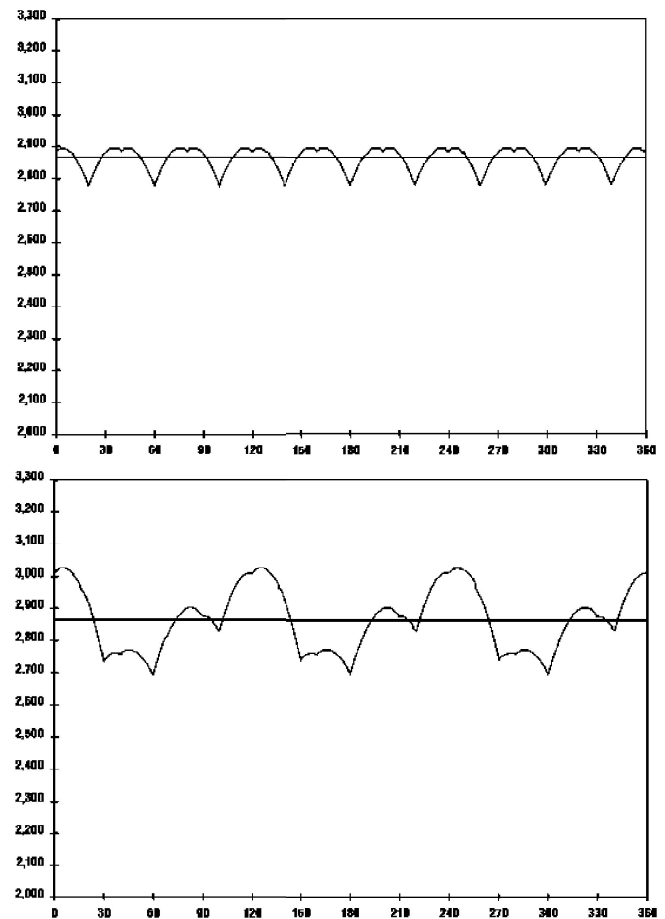


Figure 9 - A comparison between synchronized pump system (top) and non-synchronized pumping (bottom) (after Bentec, 2018)

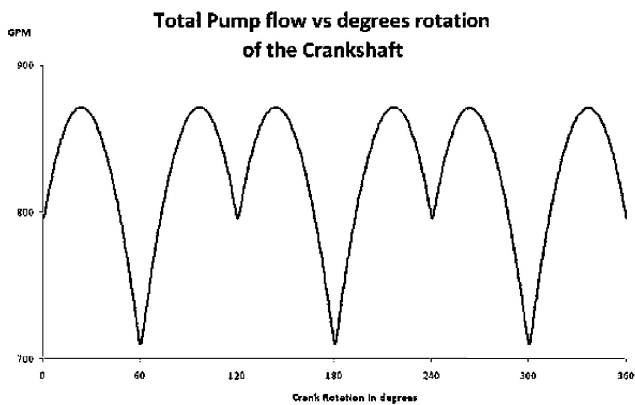


Figure 10 - Theoretical discharge flow rate of a triplex pump

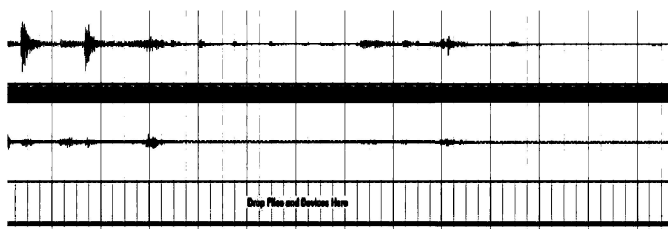


Figure 11 - Valve closing and opening generated events for a single double acting piston pump

Conclusions

This paper presented a review of main monitoring techniques with application to drilling mud pumps.

Unlike vibration monitoring, audio-based detection does not require precise instrumentation and placement. It has been shown that the audio monitoring allows not only to identify the mechanical status of the pump but can also be related to fluid dynamics within the pump, such as air entrapment detection.

A data acquisition, transfer and processing concept is proposed to better pinpoint potential equipment malfunction and allow operators to act in a timely manner while increasing safety on site and equipment lifetime.

Finally, a novel synchronization concept is proposed, which makes use of valve movement as reference instead of crankshaft positioning.

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