AN INITIAL INVESTIGATION OF THE CORRELATION BETWEEN A NUMBER OF DRILLING RELATED QUANTITIES MEASURED DURING DOWN THE HOLE DRILLING.

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Optimizing the performance for down the hole (DTH) drills is becoming increasingly important. This is due to that the industry is becoming highly competitive and therefore there is an ever-increasing demand for improving the efficiency of the drilling process. To do this, it is important to have a robust monitoring system in place that should be based on in-depth knowledge of the underlying physics of the drilling system and process. Such a system will assist drillers in improving the performance e.g. by providing recommendations concerning the settings of the drilling. To understand the performance of the system, it is very important to understand the information that can be extracted from different drilling related quantities. In this work, information obtained from the pressure signals from the feed/holdback line, impact pressure line and rotation line together with vibration signals measured with the aid of accelerometers mounted at specific locations on the drill rig are discussed. For instance, spectral properties of these quantities for good and bad drilling cases are investigated. The results indicate correlations, to some extent, between the spectral properties and the quality of the drilling.
Keywords: DTH, Performance monitoring

1. Introduction

Down The Hole (DTH) drilling is used to drill small to medium holes for oil and gas, geo thermal wells as well as for exploration drilling purposes. Down the hole drilling is a percussive drilling where there is no drill steel between the hammer and the drill bit. The drill bit and hammer unit are mounted in a cylinder and then pushed down the hole, where the percussion mechanism acts [1, 2]. The feed force and rotation are provided through tubes (also known as drill strings) screwed on to the cylinder. DTH drills are typically used for drilling holes 3000-4000 meters deep and they require low hole deviations [1, 2, 3].

Today the environmental concerns call for an increased energy efficiency of the rock drilling process and the competition in the industry propels the need for an optimization of the drilling performance. Thus, a system aiding the drillers by providing them with reliable and robust data concerning the drilling performance and its energy efficiency as well as information on how to adjust the drilling parameters to attain an increased drilling performance is urgently needed.

Such a monitoring system can assist inexperienced drillers to gain experience faster and to perform better.

In developing such a system, it is important to understand how various drilling related quantities are interrelated. Thus, in-depth understanding of the physics involved in the rock drilling process is required to enable a development of a robust and reliable monitoring system.
There exist a number of definitions of good drilling, e.g. drilling as fast as possible, drilling a specific distance during a specific time and drilling without equipment damage and minimal wear and tear.

As a measure of drilling efficiency, the concept of mechanical specific energy (MSE) associated with the excavated waste rock is frequently used [1, 4]. Optimising the drilling parameters to achieve the most cost effective rate of penetration is another method that is used in the industry [1, 5]. This method, however, only works under predictable drilling conditions and it requires a substantial amount of work to find the optimum values for the drilling parameters for different drilling conditions [1, 2].

In this study, the information obtained from the pressure signals from the feed/holdback line, impact pressure line and rotation line together with vibration signals measured with the aid of accelerometers mounted at specific locations on the drill rig are discussed. Spectral properties of these quantities for good and bad drilling cases are investigated and compared. The results indicate correlations, to some extent, between the spectral properties and the quality of the drilling.

2. Material and Methods

2.1 Experiments

The experiments were carried out on an Atlas Copco Secoroc AB Down The Hole drill. During the experiments a number of parameters were measured and recorded during good and bad drilling phases [1, 2]. The parameters taken into account are: The Rate of Penetrations (ROP), the feed line pressure (Ff), the holdback line pressure (Fh), the impact line pressure (Pimp), rotation line pressure (Prot) and vibration accelerations of the drill rig. The different pressures were measured using pressure transducers positioned at the respective lines or tubes [1, 2]. The Vibration accelerations (Acc) were measured using a triaxial accelerometer attached close to the rotation head of the drill string.

The acceleration signals were time mapped simultaneously with the different line pressures, along with the controlled changes in the Weight on Bit (WOB) which were also recorded. The triaxial accelerometer's Z-axis coincided with the direction of drilling.

3. Methods for spectrum analyses of signals

To investigate spectral properties of a discrete-time signal, x(*n*), where *n* indicates a discrete time, the power spectrum (PS) is adequate for tonal components of the signal and the power spectral density (PSD) is suitable for the random part of the signal. Welch's spectrum estimator may be used to estimate both power spectra and power spectral densities [6, 7, 1, 2].

Welch's single-sided power spectral density estimator is given by [7, 2]:

$$PSD_{xx}(k)=\frac{2}{F_s L\sum_{n=0}^{N-1}(w(n))^2}\sum_{l=0}^{L-1}\left|\sum_{n=0}^{N-1}x_l(n)w(n)e^{-j2\pi kn/N}\right|^2, 0<k<N/2-1 \tag{1}$$

where Fs is the sampling frequency, *L* is the number of periodograms, *N* is the length of the periodogram and w(*n*) is the discrete time window. The single sided power spectrum estimator is obtained by changing the scaling of the power spectral density estimator. [8, 1, 2]

3.1.1 *Time frequency Analyses*

Time frequency analyses (TFA) of signals concern signal processing methods that provide information regarding signals both in the time and in the frequency domain simultaneously. For time frequency analysis, a discrete short-time power spectral density estimator based on Welch's method is given by:

$$PSD_{xx}(k, lD) = \frac{2}{F_s \sum_{n=0}^{N-1} (w(n))^2} \left| \sum_{n=0}^{M-1} x(n) w(n-lD) e^{-j2\pi \frac{k}{N}(n-lD)} \right|^2 , 0\, k < N/2-1 \tag{2}$$

Where *lD* is the starting point for each periodogram, *D* is the overlapping increment and *M* is the length of the time series [2].

3.1.2 *The Analytic Signal and Modulation Spectrum*

The analytic signal $x_a(n)$ for a discrete-time signal $x(n)$ may be produced as [5, 2]:

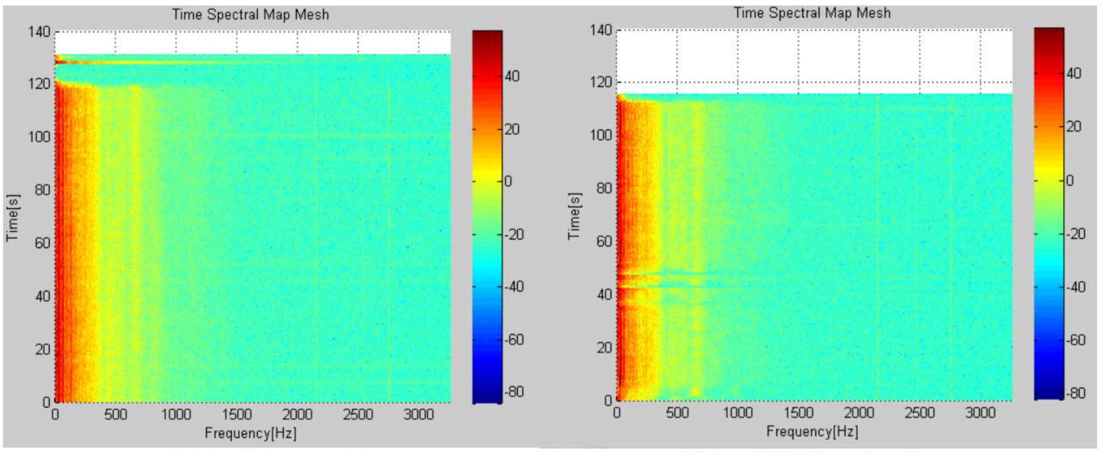
$$x_a(n) = x(n) + j * x_H(n) \tag{3}$$

where $x_H(n)$ is the Hilbert transform of $x(n)$. A modulation spectrum may e.g. be produced as the power spectrum of the magnitude of the analytic signal $|x_a(n)|$.

4. Results

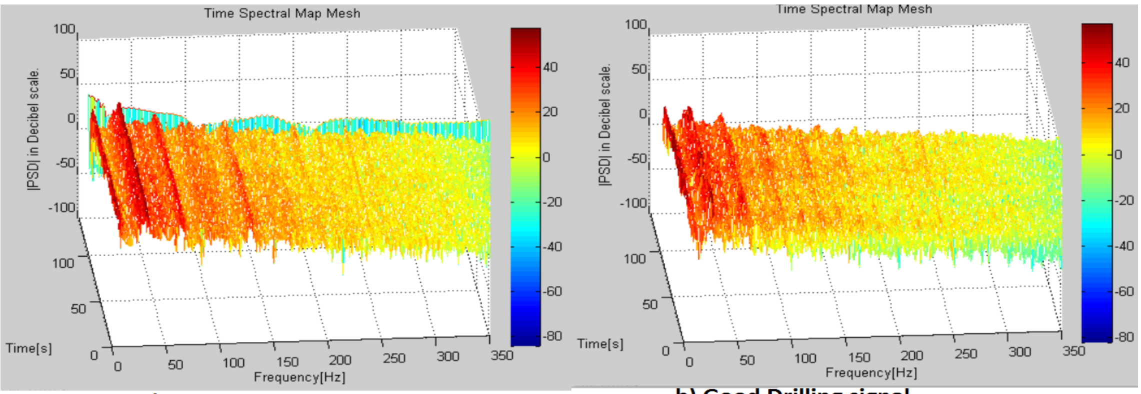
4.1 Power Spectral Density Analyses of the Rotation Pressure Line signals.

From the power spectral density estimates of the signal for the rotation line pressure presented in the spectrograms in Figs. 1 and 2, we may observe the dominating peak around 36 Hz that is basically independent of time. This is the fundamental frequency of the percussion process down the hole. Also, a number of harmonics of the fundamental frequency of the percussion process may be observed in Figs. 1 and 3. In the case of bad drilling, however, a greater number of harmonics are observable and their peaks assume higher levels compared to the good drilling where the fundamental frequency of the percussion process and the rotation frequency correspond to the dominating peaks in the spectra and the higher harmonics have less energy associated with them. The power in the signals at frequencies above 1000 Hz are almost inconsequential even though there are some stationary peaks in the spectra beyond 2000 Hz.



a) Bad Drilling signal **b) Good Drilling signal**

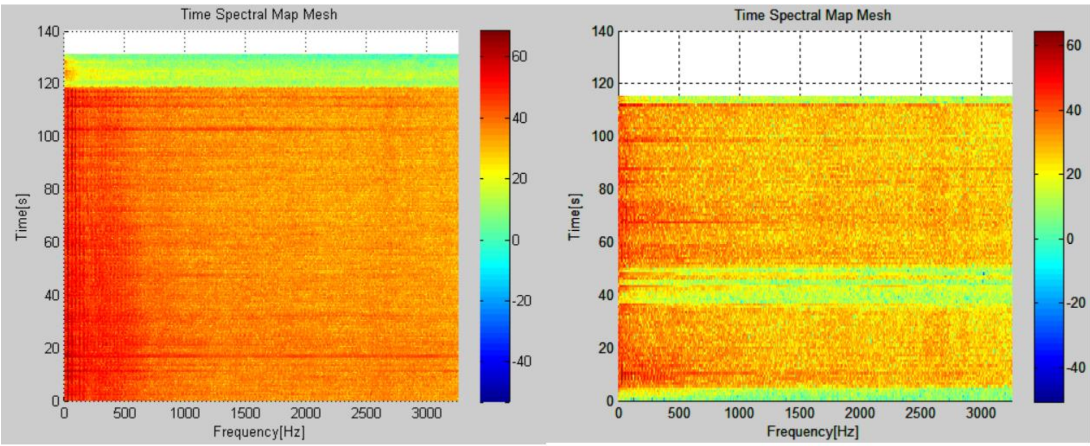
Figure **1**: Time-Power spectral density estimates in the range 0-3250 Hz, of the signal for the Rotation pressure line signal, a) Bad drilling and b) Good drilling. The colour indicates the spectrum magnitude in decibels.



a) Bad Drilling signal **b) Good Drilling signal**

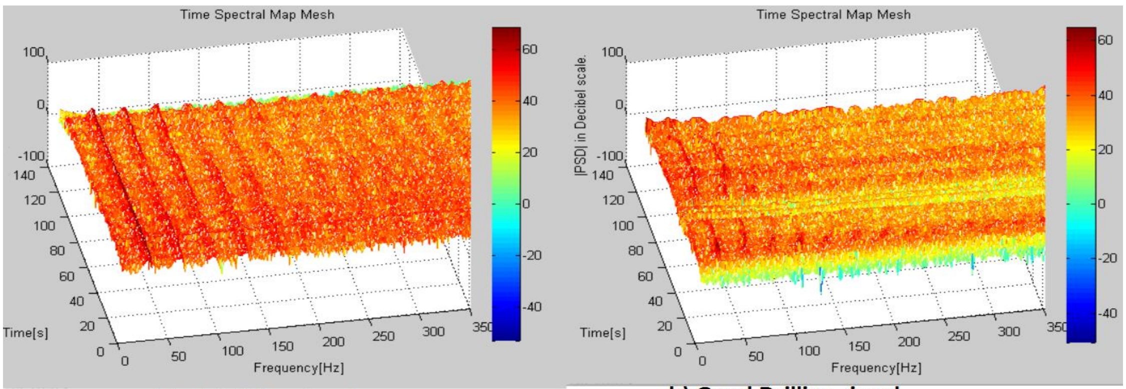
Figure **2**: Time-Power spectral density estimates in the range 0-350 Hz, of the signal for the Rotation pressure line signal, a) Bad drilling and b) Good drilling. The colour indicates the spectrum magnitude in decibels.

4.2 Power Spectral Density Analysis of the analytic signal for the vibration signals.



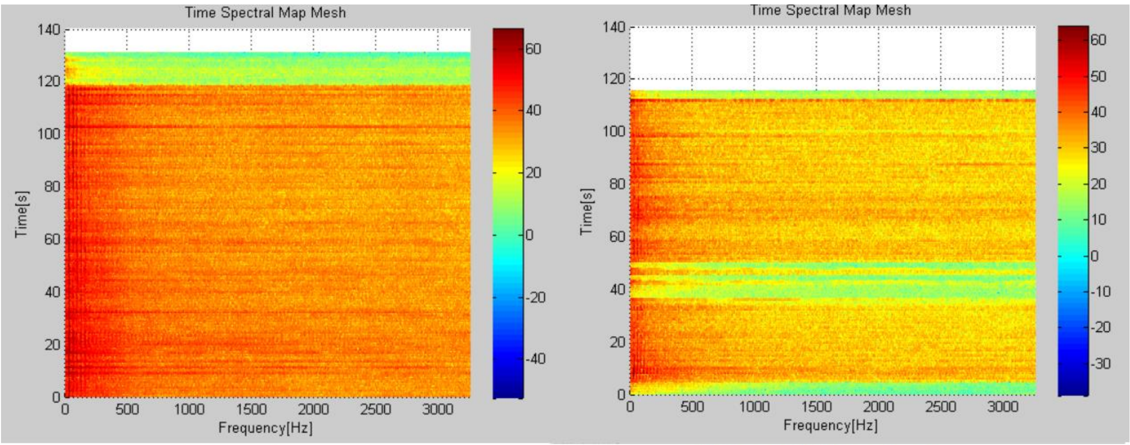
a) Bad Drilling signal **b) Good Drilling signal**

Figure **3**: Time-Power spectral density estimates of the magnitude of the analytic signal in the range 0-3250 Hz for the drilling vibration in Z-direction (Drilling), a) Bad drilling and b) Good drilling. The colour indicates the spectrum magnitude in decibels.



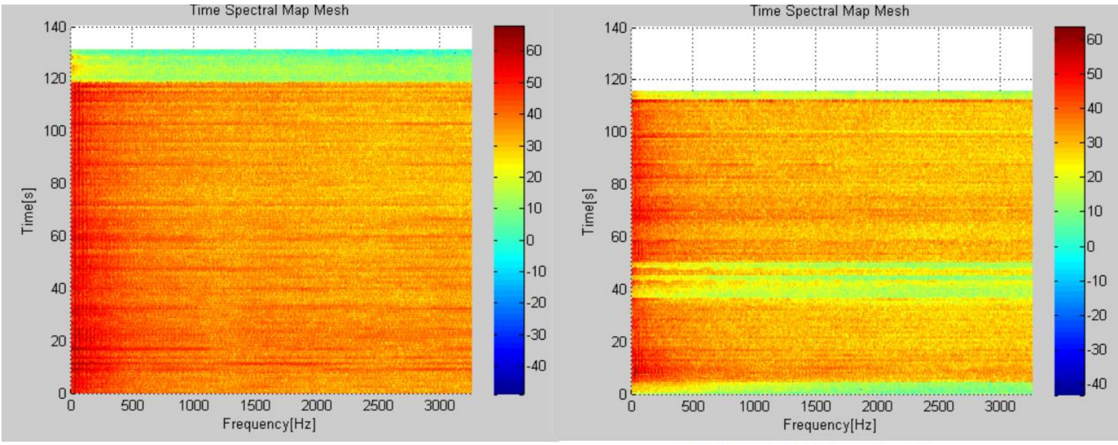
a) Bad Drilling signal **b) Good Drilling signal**

Figure **4**: Time- Power spectral density estimates of the magnitude of the analytic signal in the range 0-350 Hz for the drilling vibration in Z-direction (Drilling), a) Bad drilling and b) Good drilling. The colour indicates the spectrum magnitude in decibels.



a) Bad Drilling signal   b) Good Drilling signal

Figure **5**: Time-Power spectral density estimates of the magnitude of the analytic signal in the range 0-3250 Hz for the drilling vibration in X-direction, a) Bad drilling and b) Good drilling. The colour indicates the spectrum magnitude in decibels.



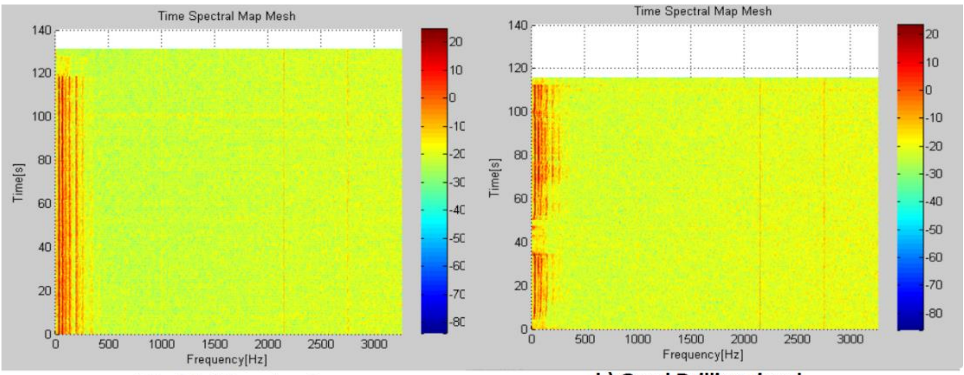
a) Bad Drilling signal   b) Good Drilling signal

Figure **6**: Time-Power spectral density estimates of the magnitude of the analytic signal in the range 0-3250 Hz for the drilling vibration in Y-direction, a) Bad drilling and b) Good drilling. The colour indicates the spectrum magnitude in decibels.

From the power spectral density estimates of the magnitude of the analytic signal for the drilling vibration presented in Figs. 3-6 it can be observed that in the Z direction (the drilling direction) the bad drilling vibration display higher magnitudes in the PSDs of their analytic signal at higher frequencies as compared to the good drilling vibration [2]. There are substantially more harmonics in the PSDs of the analytic signal for bad drilling vibration compared to the good drilling case. The same is true for the PSD estimates of the magnitudes of the analytic signals for the drilling vibrations in the X and Y directions. This is similar to the information provided by the spectrograms of rotation pressure line signals shown in Figs. 1-2.

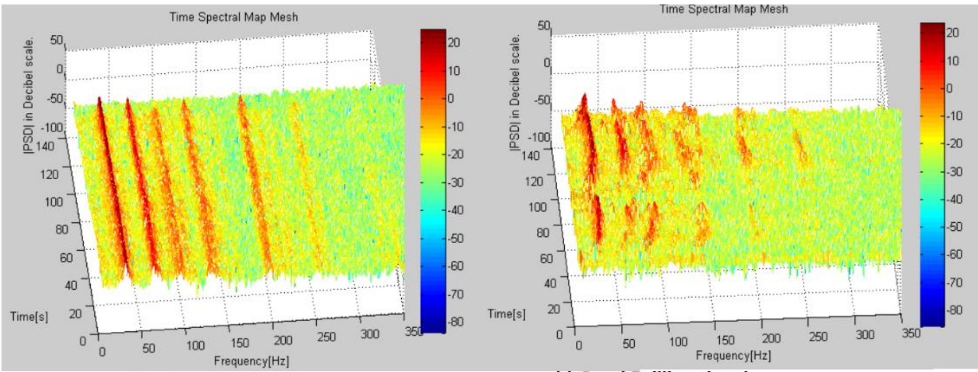
4.3 Power Spectral Density Analysis of the Impact Line Pressure signals

From the power spectral density estimates of the Impact line pressure shown in the spectrograms in Figs. 7-8, the peaks corresponding to the fundamental percussion frequency and some of its harmonics are clearly visible. This is similar to the information in the spectrograms of rotation pressure line signals shown in Figs. 3-4. In the spectrogram of the bad drilling signal, the magnitudes of the peaks of a few of the harmonics are comparable to that of the magnitude of the fundamental percussion frequency peak. In the case of a good drilling signal, on the other hand, the fundamental percussion frequency peak is dominating and the levels of its harmonics decline rapidly beyond the 2^{nd} harmonic. The power in the signals at frequencies above 1000 Hz are almost inconsequential even though there are some stationary peaks in their spectra beyond 2000 Hz.



a) Bad Drilling signal b) Good Drilling signal

Figure **7**: Time-Power spectral density estimates of the signal in the range 0-3250 Hz for the Impact pressure line signal for a) Bad drilling and b) Good drilling. The colour indicates the spectrum magnitude in decibels.



a) Bad Drilling signal b) Good Drilling signal

Figure **8:** Time-Power spectral density estimates in the range 0-3250 Hz of the Impact pressure line signal for a) Bad drilling and b) Good drilling. The colour bar indicates the spectrum magnitude in decibels.

4.4 Power Spectral Density Analysis of the vibration signals from HOPSAN simulations

Using the simulation software HOPSAN, a simple model of a down the hole drill system was made [2]. The vibration responses were taken from the same location and in the same directions as the accelerometer on the drill rig in the experiments. The bad drilling condition was obtained by increasing the feed force [2]. Generally, excessive feed force causes the drilling to become bad.

The obtained results are similar to those in sections 4.1-4.3. The fundamental percussion frequency and its harmonics are more distinct compared to the experimental counterpart which is expected since the drilling model does not account for frictional and damping losses.

In the case of bad drilling, the peaks of harmonics of the fundamental percussion frequency in the spectra display higher magnitudes particularly at higher frequencies compared to the ones associated with the good drilling case. The magnitude of the PSD estimate at the fundamental percussion frequency is lower compared to a number of its harmonics in the case of bad drilling.

In the case of good drilling, the fundamental percussion frequency peak has higher magnitude compared to its harmonics and the higher harmonics have lower magnitudes compared to the lower ones.

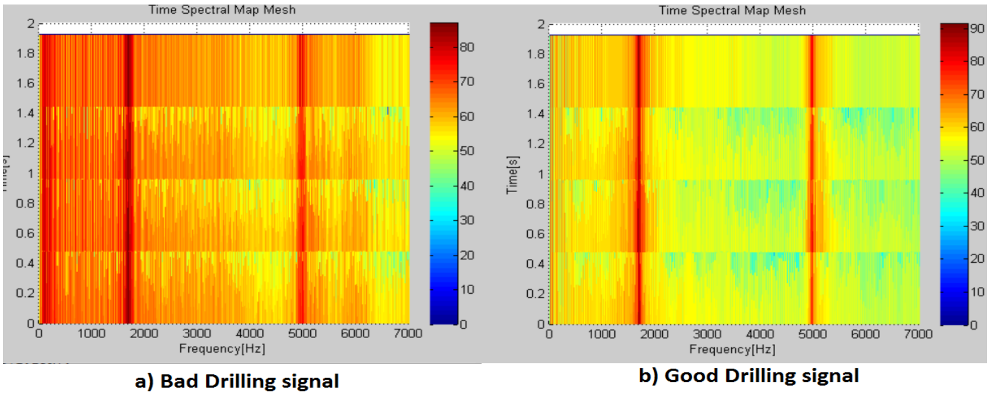


Figure **9**: Time-Power spectral density estimates in the range 0-7000 Hz of the magnitude of the analytic signal for drilling vibration obtained from Simulation of a) Bad drilling and b) Good drilling. The colour indicates the spectrum magnitude in decibels.

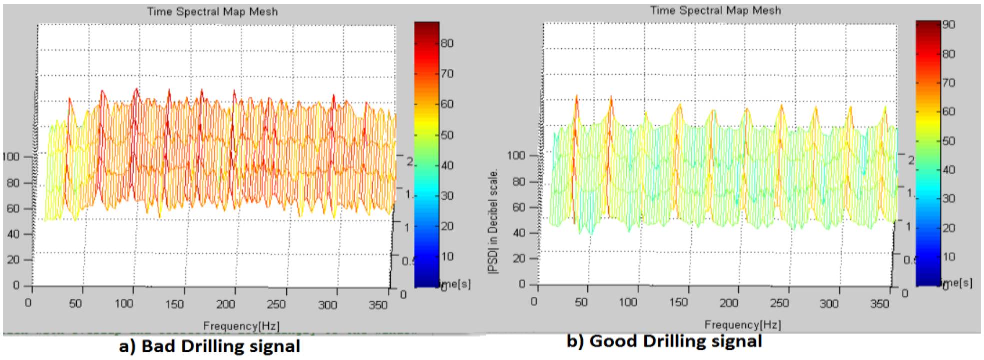


Figure **10**: Time-Power spectral density estimates in the range 0-350 Hz of the magnitude of the analytic signal for drilling vibration obtained from Simulation of a) Bad drilling and b) Good drilling. The colour indicates the spectrum magnitude in decibels.

5. Conclusions

From the results, it follows that there are definite spectrum patterns for both good and bad drillings in the drill rig vibrations, the rotation pressure and in the impact line pressures signals. We observe the fundamental percussion frequency and some harmonics in the power spectral densities in the analytic signal for drill rig vibration as well as the PSDs of various pressure signals. Figs. 3-4 illustrate that the harmonics of the fundamental percussion frequency assume higher spectrum levels at higher frequencies in the case of bad drilling [2].

For the pressure signals, the fundamental percussion frequency and its first two harmonics are dominant. The level of the harmonics of the fundamental percussion frequency in the power spectral density are very low beyond the 2^{nd} harmonic in the case of good drilling but in the case of bad drilling, harmonics beyond the 2^{nd} and 3^{rd} harmonics reach higher levels. The rotation frequency is also prominent in the spectrum of the rotation pressure. The energy at frequencies higher than 1000 Hz are almost inconsequential even though there are some stationary signals beyond 2000 Hz.

The dominating spectrum peaks in the drilling direction (Z) shown in Figs. 3-4 are at the fundamental percussion frequency and its harmonics and beyond the 2nd and 3rd harmonics. The levels of the fundamental percussion frequency harmonics decline fast in the case of good drilling. However, in the case of bad drilling, the levels of the harmonics beyond the 2nd and 3rd harmonics do not experience any fast decline [2]. The same conclusions are obtained from the spectrum of the vibration signals in the X and Y directions. From the PSD analysis of the magnitude of the analytic signals obtained from the simulations we may observe similar patterns as in the PSDs originating from experimentally measured drill rig vibrations [2].

The harmonics are more distinct and visible in greater numbers in the spectra of the signals obtained from the simulations compared to the signals from the experiments. This may be explained by the fact that the drilling simulations do not include the frictional and damping losses, etc. that are present during actual rock drilling because of the interaction between drill string, bits, etc. with the wall of the drill hole, threads between the drill strings etc. In reality, as in the experiments, the peaks of the fundamental percussion frequency and its first few harmonics are generally dominating in drill rig vibration spectra. There are also some stationary peaks in the spectra at approximately 2000 Hz and beyond that are more distinct in the PSDs from the simulations as compared to the power spectral densities originating from the measured drill rig vibration and various line pressure signals.

We can see similar patterns in the PSD analysis of the feed pressure line signals from the experiment. Few of the fundamental percussion frequency harmonics are visible as lines in the spectrogram while stationary peaks at higher frequencies are much more distinct [2].

The rotation of the drill string also affects the performance of the drilling system. The good correlation between the results obtained from the PSD estimates of the rotational line pressure and the vibration signals, that can be observed by studying Figs. 1-6, may be explained by torsional waves excited in the drill string when the drill button penetrates into the rock and the drill string is trying to rotate simultaneously.

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