Applied Acoustics 140 (2018) 275–282

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

# Analysis of signal characteristics from rock drilling based on vibration and acoustic sensor approaches

Min Qin[a,b], Kai Wang[c], Kai Pan[a], Tianxi Sun[a], Zhiguo Liu[a,*]

[a] College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China
[b] Metrology and Testing Center, China Academy of Engineering Physics, Mianyang 621000, China
[c] School of Petroleum Engineering, China University of Petroleum, Qingdao 266580, China

A R T I C L E I N F O

*Keywords:*
PDC bit
Vibration signal
Acoustic signal
Rock drilling
Lithological recognition
Signal characteristic

A B S T R A C T

Lithological recognition is of great significance in oil drilling fields. To investigate the relationship between rock properties and the vibro-acoustic signal characteristics generated by drilling, a rock drilling vibration measurement system has been developed, and a relative drilling test is conducted indoors. This paper illustrates the application of a vibration sensor and a special wideband acoustic sensor method to distinguish the specific time–frequency characteristics generated by drilling in different types of rock. Furthermore, an intuitive comparison of these two approaches is performed. In particular, an acoustic focusing device was designed to assist the wideband acoustic condenser microphone in detecting specific signals during the drilling process. In addition, time-domain and time–frequency analyses were proposed to reveal the differences in signal characteristics generated by different kinds of rock. The results indicate that both the vibration spectral characteristics and the acoustic spectral characteristics from 4 types of rock show significant differences, which may be promising for lithological recognition using the feature model. However, the acoustic sensor approach, benefiting from the specially designed acoustic focusing device, presents a better signal-to-noise ratio than the vibration sensor approach.

## 1. Introduction

Lithological recognition has a wide range of applications in oil drilling fields, such as in bit selection, optimization of drilling parameters, and early prediction of oil and gas reservoirs. Therefore, real-time identification of rock properties has been a significant research hotspot in the relevant industries [1]. Considering the fast response and unique characteristics of vibro-acoustic signals generated from rock drilling, real-time lithological recognition using vibro-acoustic signal features has become a promising method [2,3].

Numerous researchers have utilized vibration signal or acoustic signal characteristics generated by rock drilling to study lithology. For example, P. Flegner et al. considered vibro-acoustic signals generated by the drilling process of andesite, limestone, and granite under several operating modes using time and frequency signal analysis methods. In the frequency domain, the research was directed toward the possibility of using the spectrum of the accompanying vibro-acoustic signal to obtain the dynamic properties of the drilling process [4]. Moreover, the acoustic identification of rocks during the drilling process was studied by Zborovjan et al. [5] and Miklusova et al. [6]. They found that the processed acoustic signals obtained during rotary drilling using the Fourier transform could be employed to control the rock breaking process. Noise characteristics of drill bits during the drilling process were analyzed by Gradl et al. [7]. It was reported that bit characteristics can be determined using acoustic data, i.e., the noise of a bit (Roy and Adhikari) [8]. B. Rajesh Kumar [9] predicted rock properties based on the sound level produced during rock drilling. His study was carried out to develop empirical relations using multiple regression analyses between the sound level produced during drilling and rock properties, considering the effects of the drill bit diameter, drill bit speed and drill bit penetration rate. H. Vardhan et al. [10] investigated the usefulness of the sound level in determining rock or rock mass properties, such as the compressive strength, using a jackhammer drill at a laboratory scale by fabricating a jackhammer drill setup in which the applied thrust can be varied while vertical holes are drilled. Moreover, several authors have concentrated on the variation in spectral amplitudes of acoustic waves over a wide band of monitoring frequencies with an increasing applied stress [11–16]. Additionally, the acoustic emission characteristics of rock breaking have also been broadly studied. For example, M. Karakus [17] determined a relationship between acoustic emission (AE)

* Corresponding author.
*E-mail address:* liuzhiguo512@126.com (Z. Liu).

https://doi.org/10.1016/j.apacoust.2018.06.003
Received 20 December 2017; Received in revised form 21 April 2018; Accepted 4 June 2018

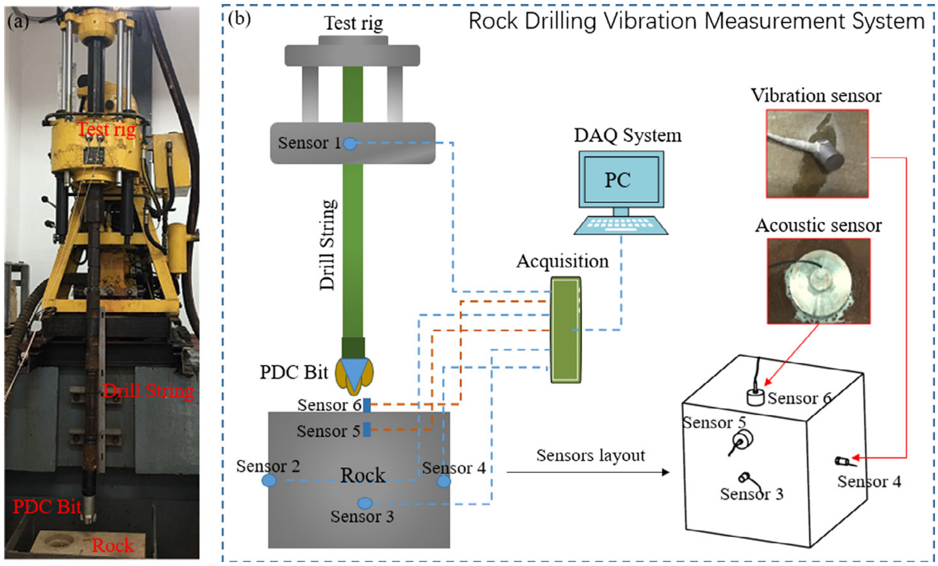


**Fig. 1.** (a) Laboratory rig and (b) schematic of the rock drilling measurement system.

signals and diamond drill bit wear. By analyzing the characteristics of acoustic signals generated while drilling in different types of rock, it is possible to obtain useful information by using specific algorithms and models for lithology identification. In B. Rajesh Kumar's work, multiple regression and artificial neural network (MLP and RBF) models were used to predict rock properties [18]. While past studies have concentrated on either vibration sensor or acoustic sensor approaches, this research primarily investigates the differences in signal characteristics based on the above two approaches as well as the advantages and disadvantages of these two approaches. In particular, past studies of lithological recognition using the acoustic sensor approach are primarily focused on the sound level, regardless of the frequency spectral characteristics of the signal, which may not be available in strong background noise situations. Consequently, an acoustic focusing component was designed to assist the wideband acoustic condenser microphone in detecting the acoustic signal under a strong background noise environment. A wideband time–frequency domain analysis was applied to the acquired sound signal to obtain the frequency spectrum differences of various rocks.

In this paper, the signal characteristics obtained from a drilling process in different types of rock using a polycrystalline diamond compact (PDC) bit are studied with vibration and acoustic sensor approaches under a complex background noise environment. In particular, an acoustic focusing component is designed to assist the wideband acoustic condenser microphone in detecting specific signals during the drilling process. In addition, the time-domain and short-time Fourier transform (STFT) analytical methods are used to distinguish the specific signals stimulated during drilling. Moreover, a multiband digital filter is used to maximize the acquisition of the drilling signal in a strong background noise environment. Finally, the advantages and disadvantages of these two approaches are compared.

## 2. Measurement principles

The PDC bit acts on a rock to break it by shearing forces, and the energy generated by the rock shear fracture process is usually characterized as shear rupture energy [19]. In the drilling process, the energy used for breaking rocks is derived from the torque generated by the rotation of the drill bit and the accompanying axial pressure force. These two energy sources are completely consumed by rock breakage, friction heat generation, sound, etc. The energy consumption from the interaction between the drill bit and the rock formation primarily consists of two parts. Part of the energy is used to break the cement in the rock, and the remaining energy is used to break the main minerals. Therefore, the vibration frequency spectrum of the rock breaking also contains the characteristic frequency spectrum of the cement and the characteristic frequency spectrum of the main minerals [20–23]. Due to the different compositions of cement and main minerals in different types of rock, the frequency spectra of rock disintegration will vary. Therefore, lithological recognition based on differences in the frequency spectra of different types of rock becomes possible.

Vibro-acoustic signals are collected using vibration or acoustic sensors and are further transformed to electrical signals and delivered to a computer system after amplification. STFT analytical methods are adopted to process the signal to analyze the frequency spectrum [24]. The STFT provides a 2-D time–frequency domain for the variation of all frequencies contained in the vibration signal. The magnitude of the STFT of the vibration signal y(t) is defined as in [25]:

$$\mathrm{TF}(t, f) = \left| \int_{-\infty}^{+\infty} y(\tau) h^{*}(\tau - t) e^{-i2\pi f\tau} d_{\tau} \right|. \quad (1)$$

where y(t) is the original signal; h(t) is a short-time analysis window centered at t = 0. The width of h(t) should be large enough to achieve a high frequency resolution on the time–frequency distribution, allowing adjacent frequencies to be distinguished from each other. The STFT reflects the energy distribution in the time–frequency plane.

A digital filter is selected to process the signal, which is a difference equation consisting of the time-domain signal input and output sequence. The transfer function of the digital filter system is [26]

$$\mathrm{H}(z) = \frac{\sum_{0}^{M} a_{1k} z^{-k}}{1 + \sum_{k=1}^{N} b_{1k} z^{-k}}. \quad (2)$$

where H(z) is the transfer function; *N* is the filter order; *M* is the number of zeros in the filter transfer function; and $a_{1k}$ and $b_{1k}$ are coefficients of the weight function.

## 3. Experimental setup and measurement techniques

### 3.1. Experimental realization

The rock drilling vibration measurement system includes an experimental drilling rig, rocks, a data acquisition system, etc., as shown in Fig. 1b. The laboratory rig, shown in Fig. 1a, primarily consists of a power system, control system, water circulation system, drill string, and drill bit. The control system sends a command to rotate the drill string