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Optimizing sampling frequency of surface and downhole measurements for efficient stick-slip vibration detection

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ABSTRACT

Drilling vibrations significantly impact drilling operations with high costs due to early downhole equipment failure and loss of productive time. Stick-slip vibrations, a severe form of torsional vibrations, is known to be present up to 50% of total drilling time, making it a topic of immense concern and research. An ongoing discussion in the industry is regarding the reliability of surface measurements for early detection of severe downhole bit sticking. Moreover, most surface measurements are sampled at lower frequency rates closer to 1 Hz. Recently, the implementation of advanced data acquisition modules in downhole subs has greatly improved our understanding of drilling vibrations through high resolution data, sampled up to 10 kHz. However, with a wide range of sampling frequency to choose from different available tools, a critical question remains unanswered. What is an optimal and adequate sampling frequency for early detection of downhole vibrations using both surface and downhole measurements? The paper addresses the question with a focus on stick-slip vibrations through an experimental investigation. Stick slip tests are repeated for different sampling frequencies of surface and downhole measurements and the stick slip index for each case is calculated. The stick-slip index varies for different sampling frequency even though the vibration tests remain completely identical. It was inferred that sampling frequency of measurements greatly impact the detection of downhole vibrations. Even though stick-slip vibrations are characteristically low frequency vibrations ($\leq$2Hz), a minimum of 10Hz sampling frequency is recommended for detection of stick-slip vibrations. Moreover, all characteristics of stick-slip vibrations including bit sticking, bit RPM peaks and negative bit RPMs are clearly observed at a minimum of 100Hz sampling rate.

1. Introduction

Drilling is an integral part of oil and gas exploration and development that involves both high expenditure and risk. As a result, technological advancements that help make the drilling process more efficient, improve well quality and prolong downhole tool life are sought-after in the drilling industry. One such avenue of research has been drilling vibrations. Being the source of multiple drilling problems and the major cause for reduced rate of penetration, research on drilling vibrations has spanned for greater than 70 years [1]. Research efforts include dynamic modeling of the drillstring, analyzing hours of recorded field data, experimental investigation, and implementation of passive and active control strategies [2–4].

Drillstring vibrations are defined based on direction of appearance in three distinct categories [7]. Namely, axial vibrations (bit-bouncing), lateral vibrations (bit and drillstring whirl) and torsional vibrations (stick-slip phenomenon). The modes of vibration are summarized in Fig. 1 along with their respective characteristic frequency. However, with better downhole tools and data acquisition methods, the understanding of downhole vibrations has changed drastically. For example, while stick slip is seen as a low frequency vibration mode, torsional oscillations along the drillstring have been characterized up to 500Hz. While high-frequency torsional oscillations and stick-slip vibrations may originate

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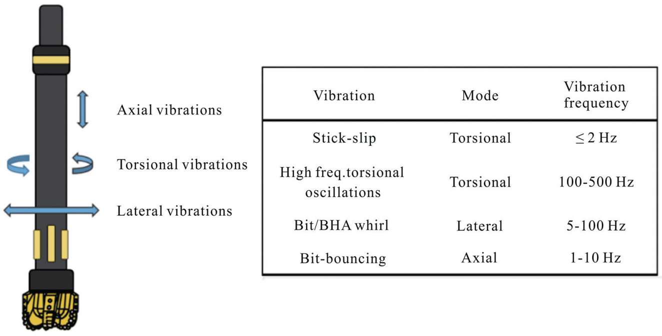


Vibration	Mode	Vibration frequency
Stick-slip	Torsional	≤ 2 Hz
High freq.torsional oscillations	Torsional	100-500 Hz
Bit/BHA whirl	Lateral	5-100 Hz
Bit-bouncing	Axial	1-10 Hz

Fig. 1. Major vibration modes and associated characteristic frequencies [5,6].

independently, multiple sources of vibrations have been identified that are coupled in nature, for example, coupled axial and stick-slip vibrations and bit chatter. Dong and Chen [1] present a detailed summary of possible classifications of drillstring vibrations.

Interestingly, data acquisition tools and sensors have adapted to high-frequency downhole measurements by utilizing downhole data storage solutions. Currently, in the industry, downhole tools exist that can acquire and store downhole parameters such as weight on bit, downhole torque, bit RPM, bit acceleration, temperature, pressure etc. at sampling rates of up to 5120 Hz and higher [8]. While such high-resolution data is immensely helpful for research and post drilling scrutiny, the tools do not provide real-time feedback, are expensive to run and require data management solutions. One possible answer is to develop downhole processing of data that helps in summarizing a large volume of data into unique statistical parameters that help in downhole vibration detection. Another solution is to develop an optimal sampling strategy that is adequate for real-time monitoring of downhole conditions. This can be applied at both the surface and bit level. Fig. 2 presents a review of sampling frequency literature used in field and laboratory setting for surface and downhole measurements. The Y-axis in Fig. 2 represents the sampling frequency (in logarithmic scale). The suggested minimum requirement for successfully detecting different modes of drill string vibrations have also been marked. While high sampling frequencies help in detecting all modes of vibrations in the drillstring, not all vibration modes cause severe damage/loss of performance. A broad spectrum of sampling frequency is used in the industry, as seen in Fig. 2. Ultimately, the choice of sampling frequency should be based on vibration mechanism being analyzed. Table 1 provides further insight regarding downhole sensors and data acquisition methods utilized.

The paper focuses on torsional stick-slip phenomenon, one of the most detrimental modes of drilling vibrations. Light is shed on data acquisitions systems, sampling theory and the problems with under-sampling as well as over-sampling surface and downhole measurements. In doing so, the effect of high-frequency measurement on detection of stick-slip vibrations is discussed through extensive experimental tests. Lastly, an optimal sampling frequency is estimated that helps in recognition of low frequency and high frequency bit sticking through both surface and downhole measurements.

2. Stick-slip vibrations

Stick-slip is a form of severe torsional vibrations that lead to large fluctuations in bit RPM. Stick-slip is often undetected at the surface due to constant top drive rotations. However, the bit RPM undergoes stick and slip phases. It is found to be present during 50% of drilling time [9,10]. The phenomenon occurs when the rotational torque in the drillstring is not sufficient to overcome the torque at bit due to rock-bit interaction and friction between the drillstring and the wellbore. The slip phase is initiated when the built-up torque is enough to overcome the static friction during which, the bit RPM can shoot up to 10 to 15 times the top drive RPM [11]. In some severe cases, negative RPM/rotation of the bit has also been recorded. The resultant high rotational speed and bit acceleration has been known to cause premature BHA equipment fatigue and failure (see Fig. 3). Stick-slip is also a well-known cause of drill bit

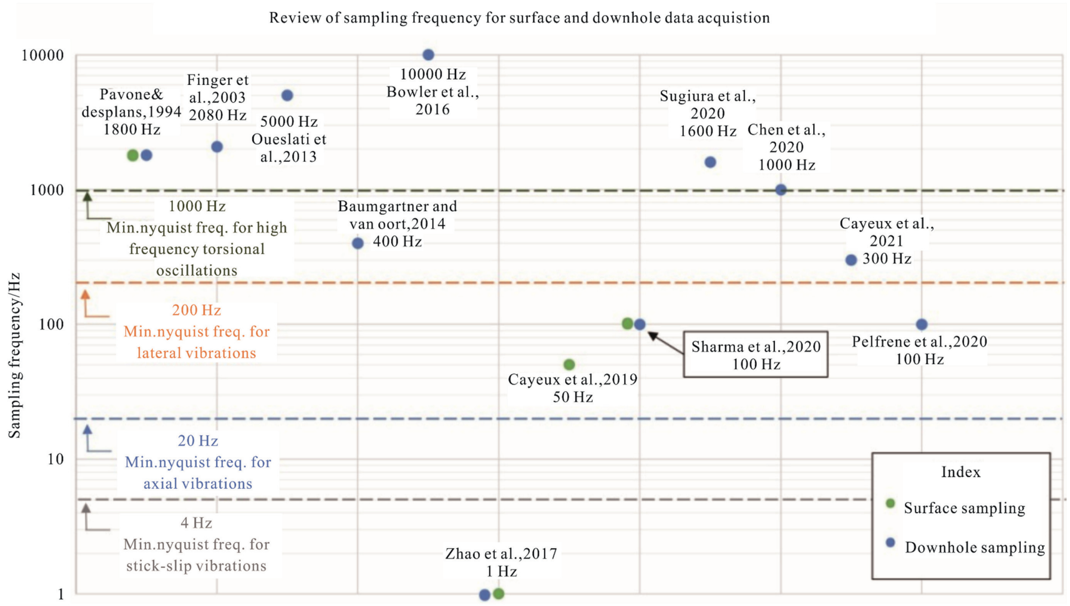


Fig. 2. A review of sampling frequency for surface and downhole measurements with associated limits for detecting drill string vibrations.

Table 1
Summary of vibration detection tools.

Reference	Tool	Data acquisition location		Sampling frequency	Data scquisition, transmission & storage
		Surface	Downhole		
Pavone and Desplans, 1994 [23]	Downhole sub with accelerometer, magnetometers, temperature, pressure, and weight on bit sensors	✓		1800 Hz	Continuous transmission Wired drillstring
Finger et al., 2003 [24]	Sub equipped with accelerometers, magnetometers, pressure sensor, load sensor, torque sensor and temperature sensor.		✓	65–2080 Hz	Real-time wired drillstring
Oueslati et al., 2013 [25]	Vibration sensor at bit		✓	1400 Hz (Field), 5000 Hz (Lab)	Not reported
Baumgartner and Van Oort, 2014 [26]	Radially oriented accelerometer at bit		✓	Up to 400 Hz (in bursts)	Not reported
Bowler et al., 2016 [27]	Sub equipped with accelerometers, magnetometers, gyroscopes, inclinometers, pressure sensor, load sensor, torque sensor temperature sensor.		✓	10000 Hz	Data stored downhole
Zhao et al., 2017 [28]	Not available	✓	✓	0.5–1Hz	Not reported
Millan et al., 2019 [11]	Downhole shock sensors	✓	✓	10–50 Hz	Not reported
Sugiura et al., 2020 [29]	Hockey-puck-shaped sensor package with accelerometers, magnetometers, gyroscopes, and temperature sensor installed at the bit		✓	20–1600 Hz	Burst/Continuous data storage
Chen et al., 2020 [30]	Sub equipped with accelerometers, magnetometers, gyroscopes, inclinometers, and a temperature sensor		✓	1000 Hz	Data recorded & stored downhole
Pelfrene et al., 2021 [31]	Sensor package with accelerometers, gyroscope, and temperature sensor installed in the bit shank or BHA		✓	100 Hz	Data storage
Cayeux et al., 2021 [32]	Sub equipped with three-axis accelerometers, gyro, and magnetometers		✓	200Hz, 300 Hz	Data recorded & stored downhole

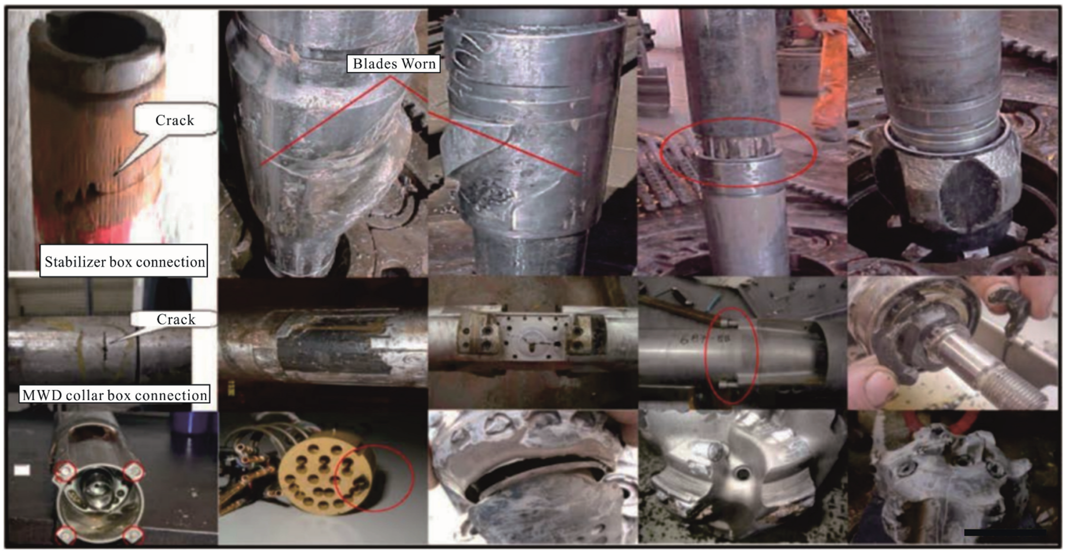


Fig. 3. Downhole tool damage caused by stick-slip [14].

damage [12,13]. These adverse effects of stick slip vibrations lead to an increase in NPT and loss of revenue.

One of the first to recognize and analyze stick-slip using experimental data recording tool was done by Cunningham [15], and since then, a lot of research work has been focused on studying and mitigating this drilling dysfunction. Mathematical modeling including the lumped parameters models, single degree of freedom and multiple degree of freedom models have been developed to analyze stick-slip and other drillstring vibrations [7,10,16–19]. Although some modeling approaches include the complicated drillstring dynamics [20,21], most models are low fidelity models in nature, and they lack an accurate representation of the system dynamics because of the complexity and non-linearity of drillstring and wellbore interaction [3]. Experimental downscaled drilling setups have been used extensively, with great success for parametric investigation of drilling dysfunctions [4]. Another approach that has been widely used is to record high-frequency downhole measurements for post drilling analysis. Downhole data acquisition tools capable of recording high-frequency downhole measurements are becoming more readily available. The data recorded on-board these tools can be used to paint an accurate real-life picture of the downhole drilling dynamics and dysfunctions. Additionally, this readily available downhole data has also aided machine learning applications in the drilling industry as high sampling frequency improves the resolution and quality of data collected [22].

3. Data acquisition and sampling

Drilling is a dynamic process which involves multiple process parameters including weight-on-bit (WOB), torque, drillstring RPM, rate-of-penetration (ROP) annular pressure, annular temperature, etc. Continuous measurement and analysis of drilling parameters plays a crucial role in carrying out a safe and efficient drilling operation. In the past, downhole measurements made using wireline measurement systems could not be utilized for real-time drilling optimization. With the introduction of measurement while drilling (MWD) tools, it became possible to measure drilling parameters and use them in process control. Today with the advancements in technology, state-of-the-art data acquisition systems (DAQ) are used to monitor and analyze drilling operations. This has helped in optimizing drilling, which in turn has resulted in cost reduction and reduced non-productive time (NPT).

3.1. Data acquisition system

Data acquisition (DAQ) systems are electronic/computer systems that are used to measure and acquire real-world physical signals and convert them into digital data that can be processed by a computer. A standard DAQ system consists of four basic components as shown in Fig. 4 (see Fig. 5).

(1) Sensors/transducers: Sensors detect the changes in the physical environment and generate a corresponding electrical signal. In a drilling system some of the sensors used are gyroscopes, accelerometers and magnetometers (to measure RPM, vibrations, inclination etc.); load cells (to measure system load, WOB); pressure sensors; torque sensors etc.
(2) Signal conditioners: The raw signals from the sensors must be conditioned/cleaned before they can be processed further. Signal conditioners are used to filter the unwanted noise out of the signals thus achieving a desired signal-to-noise ratio. They can also be used to amplify very-low voltage signals, for example, signals from a strain gauge-based sensors often have very low voltage output (millivolts (mV) range) which must be amplified before it can be processed. Signal scaling is another common signal conditioning application.
(3) Analog-to-Digital Converter (ADC): The analog signals from the sensors are digitized so that they can be interpreted by a computer. ADCs are electronic systems that perform quantization and sampling on the analog signal to convert it to a digital signal.
(4) Computer: This is the final component of the DAQ system and it's where all the incoming digital data is integrated with software. The data can be stored in memory for future analysis or can be used in real-time to display the process parameters or as input/feedback to control loops in the system.

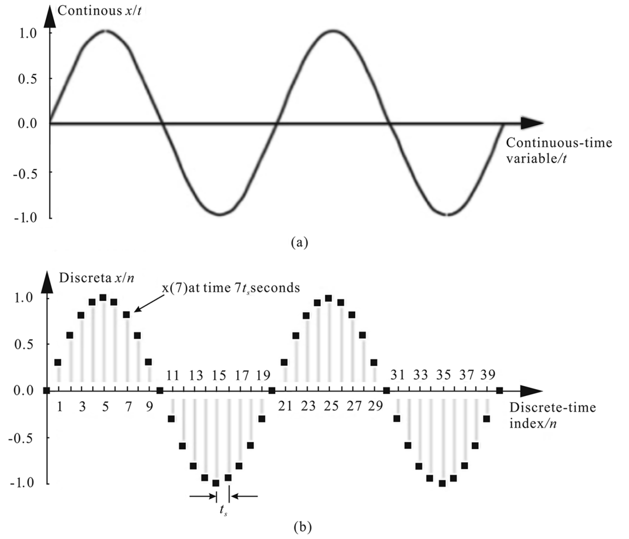


Fig. 5. (a) A continuous time domain sine wave; (b) discrete sample representation [33].

3.2. Sampling theory

The world we live in is analog. All the physical quantities we perceive or measure around us in nature, like sound, pressure, temperature, voltage etc., are analog i.e., they are continuous in time. A variety of sensors/transducers can be used to acquire these physical quantities and convert them into electrical signals containing useful information and data. These electrical analog signals must be digitized to make them accessible for computers to process the data contained in them and this is where the concept of data sampling comes into play.

Sampling is the process of digitizing an analog/continuous signal in time by acquiring discrete amplitude values (samples) of

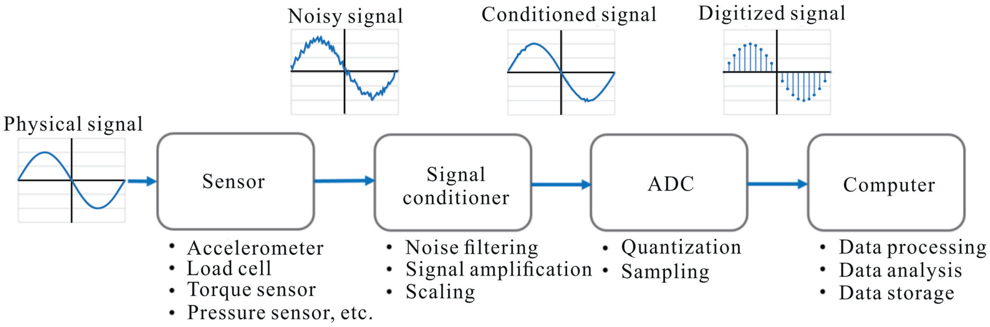


Fig. 4. A standard DAQ system.

the signal at regular intervals of time. Sampling frequency, measured in hertz (Hz), is the number of samples collected every second. For example, digital audio is sampled at rate of 44,100 Hz, this means the analog audio signal from a device like a microphone is sampled 44,100 times a second or 44,100 discrete samples are recorded every second at fixed intervals of time. This time interval is called the sampling interval (t_s) and is the inverse of the sampling frequency.

This approach of sampling analog signals uniformly over constant time intervals is the more traditional method of sampling. Other non-uniform or irregular sampling techniques also exist and are advantageous in situations where power and/or memory consumption are constrained [34,35].

3.3. Nyquist-Shannon sampling theorem

Claude Shannon's work at the Bell Labs in 1948, built upon the work of others including Harry Nyquist and Edmund Taylor Whittaker and formalized the concept of periodic sampling as we know it today. In his 1948 article titled ‘A Mathematical Theory of Communication’ [36], Shannon stated:

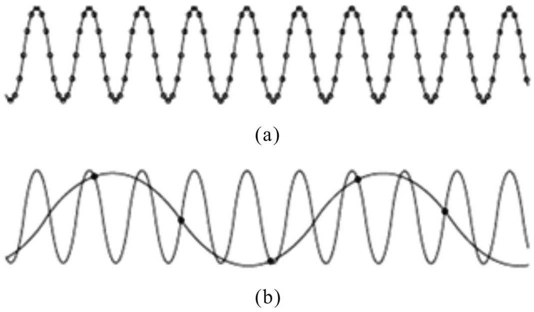
> *If a function of time f(t) is limited to the band from 0 to W cycles* per *second it is completely determined by giving its ordinates at a series of discrete points spaced* $\frac{1}{2W}$ *seconds apart.*
>
> *Let f(t) contain no frequencies over W. Then*
>
> $$f(t) = \sum_{-\infty}^{\infty}\left(X_n \cos\frac{sin\ \pi(2Wt-n)}{\pi(2Wt-n)}\right)$$
>
> *where,*
>
> $$X_n = f\left(\frac{n}{2W}\right)$$
>
> *and* X_n *is the nth sample.*

This is the basis of the Nyquist-Shannon sampling theorem which states that, to avoid aliasing and loss of information the sampling rate required to sample an analog signal must be at least twice the highest frequency (bandwidth) of the signal. This minimum required sampling rate is known as the Nyquist rate.

3.4. Over-sampling and under-sampling

According to the sampling theory, to retain all the information in a band-limited analog signal, the signal has to be sampled at a frequency which is at least double the highest frequency component of the signal. Sampling an analog signal below the Nyquist rate results in loss of information, also known as signal aliasing. Fig. 6(a) shows a sine wave sampled with adequate sampling frequency, thus preserving the information in the signal. On the other hand, in Fig. 6(b), the same sine wave is under-sampled and the resultant sampled signal has a frequency component much lower than the original signal, therefore the signal is aliased.

With the advancements in technology, the capabilities of data acquisition systems have increased exponentially over the years, which has made it possible to sample data at higher and higher rates. When a signal is sampled at a rate higher than the Nyquist rate, the signal is said to be over-sampled. It is known to improve the signal to noise ratio and resolution and help in overcoming aliasing but on the other hand it requires more power and memory to process the incoming signals.


(a)

(b)

Fig. 6. (a) Adequately sampled sine wave; (b) Under-sampled sine wave [source: ni.com].

4. Investigation of optimal sampling frequency for vibration detection

Investigation of drilling vibrations using a high frequency data acquisition system for surface and downhole measurements has been carried out using an experimental downscaled test rig. Advantages of using a downscaled setup for stick-slip investigation include controlled and repeatable testing conditions and real-time downhole measurements.

4.1. Experimental setup

The experimental setup is a laboratory scaled drilling test rig designed and built to simulate a full-size drilling rig. The setup is equipped with several sensors and actuators which help to monitor and control the drilling process. A stepper motor coupled with a ball screw linear actuator acts as the hoisting mechanism and the linear displacement is measured by a linear displacement sensor. A 18V DC motor is used to function as the top-drive motor. Multiple rotary encoders are used to measure the RPM at the top and the bottom of the drillstring. A load cell measures the weight-on-bit and a torque sensor is used to measure the torque on the drillstring. The sensors and actuators are all connected to a National Instruments data acquisition card which is further connected to a computer running National Instruments LabVIEW. The setup can be monitored and controlled using the LabVIEW virtual instrument. Fig. 7 shows a basic schematic of the setup.

The details of the experimental setup including the physical structure and instrumentation aspects are included in Sharma et al. [37].

The BHA of the test rig consists of an electromagnetic brake which is instrumental in creating a programmable bit torque sequence, simulating an actual-rock bit interaction [4]. When activated, the electromagnetic brake installed at the BHA induces a non-linear frictional torque that opposes the motion of the drillstring. The magnitude of the torque applied by the brake can be increased by adjusting the current input to the brake. To recreate stick-slip vibrations observed during drilling a rock formation, two vibration scenarios are considered. The two vibration scenarios help in distinguishing the intensity of resultant disturbance in the drillstring post a stick-slip cycle. Namely, the two testing scenarios include.

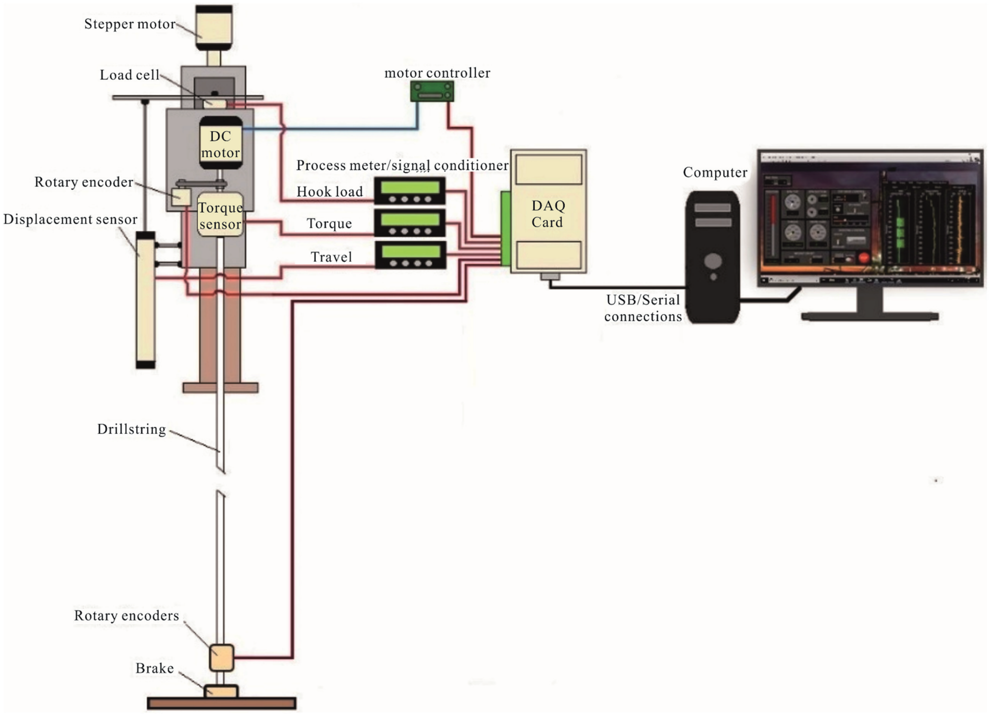


Fig. 7. Experimental setup.

(1) Low frequency bit sticking/Severe stick-slip vibrations:
In this test scenario, the bit undergoes a long sticking period of up to 5 s. As a result, stick-slip cycles can be characterized as a low frequency phenomenon of characteristic frequency ≤ 0.02 Hz. Low frequency bit sticking can also be interpreted as severe stick-slip vibrations as longer sticking periods result in higher rotational energy storage in the drillstring which is released suddenly in the slip phase causing high peaks in bit RPM.

(2) High frequency bit sticking/Mild stick-slip vibrations:
This vibration scenario is identified by fast and abrupt bit stick and slip cycles. As a result, this test scenario induces vibrations with characteristic frequency of 1Hz. With less than 1 s sticking, the resultant wave of disturbance in the drillstring is less than low frequency bit sticking.

5. Results

The following section presents the experimental results of the two stick-slip vibration testing scenarios described as high and low frequency bit sticking. For each testing scenario, three identical tests are carried out at 1, 10 and 100 Hz sampling frequency. The measured parameter from the test includes surface and bit RPM, top drive torque and weight on bit. For each sampling frequency, two plots are generated. One for surface torque with respect to time and other for bit and surface RPM with respect to time. For each scenario, a measure of the severity of the torsional vibration is defined through the stick-slip index (SSI) [38]. SSI is defined as:

$$SSI(Stick-slip\ index) = \frac{Bit\ RPM_{max} - Bit\ RPM_{min}}{2 \times Bit\ RPM_{avg}}$$

SSI values greater than 1 represent pure bit sticking. With SSI = 1 or higher, the bit RPM swings from 0 to at least twice the average bit rotational speed. Since the SSI values are dependent on bit RPM swings, higher SSI values correlate to greater deviation from average. This metric will be used to discuss severity of torsional vibrations in the results obtained. The characteristics of stick-slip vibration include bit speed dropping down to zero (bit-sticking), large and sudden peaks in bit RPM and negative bit revolutions.

5.1. High frequency bit sticking/Mild stick-slip vibration results

Due to the nature of high frequency vibrations, the bit sticking period is less resulting in milder stick-slip vibrations than low frequency bit sticking vibrations. The three test cases for high frequency bit sticking at 1, 10 and 100 Hz are plotted from Figs. 8–10. Interestingly, the vibration signature is different for all

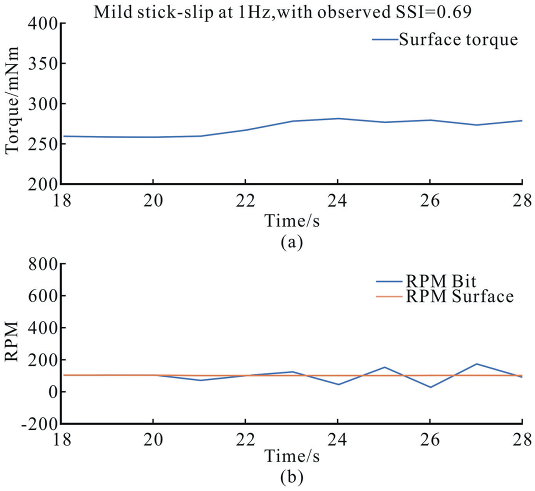


Fig. 8. Surface torque vs time (top), surface and bit RPM vs time (bottom) for test at 1 Hz sampling.

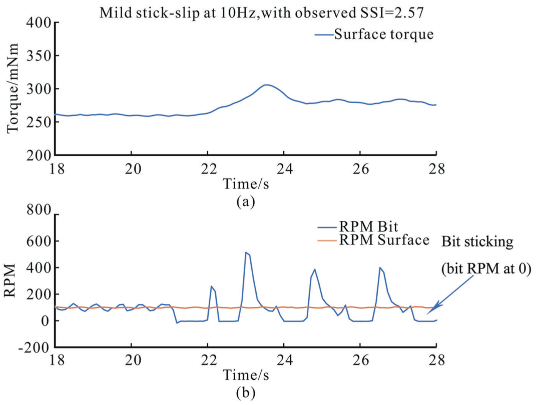


Fig. 9. Surface torque vs time (top), surface and bit RPM vs time (bottom) for test at 10 Hz sampling.

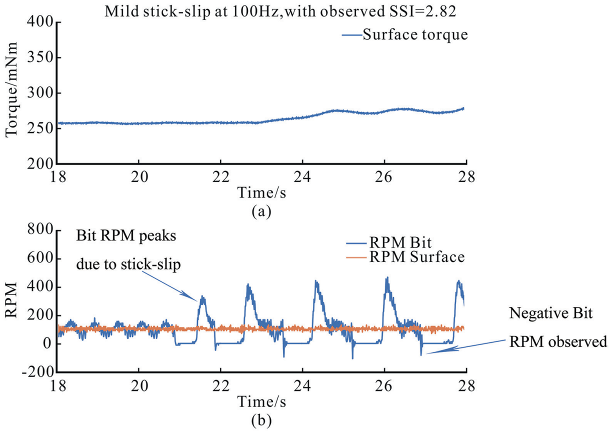


Fig. 10. Surface torque vs time (top), Surface and bit RPM vs time (bottom) for test at 100 Hz sampling.

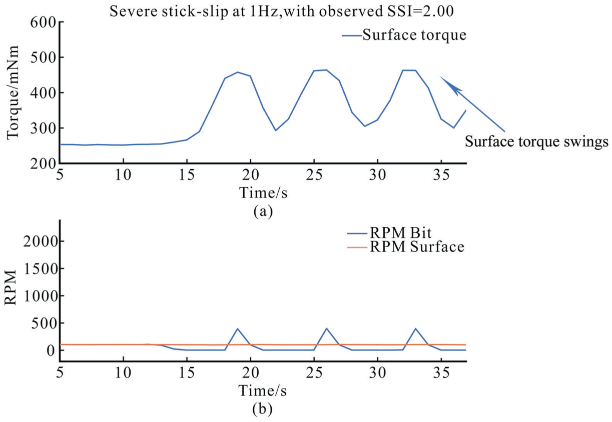


Fig. 11. Surface torque vs time (top), surface and bit RPM vs time (bottom) for test at 1 Hz sampling.

the three cases of sampling frequency. Overall, the test in Fig. 8, sampled at 1 Hz looks smooth with low noise interference whereas test case in Fig. 10 has the most noise due to higher sampling frequency.

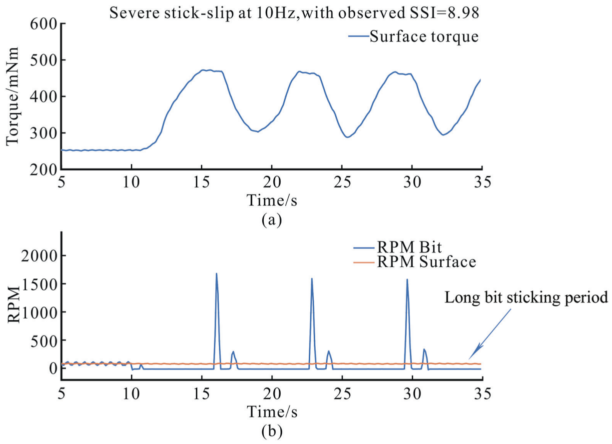


Fig. 12. Surface torque vs time (top), surface and bit RPM vs time (bottom) for test at 10 Hz sampling.

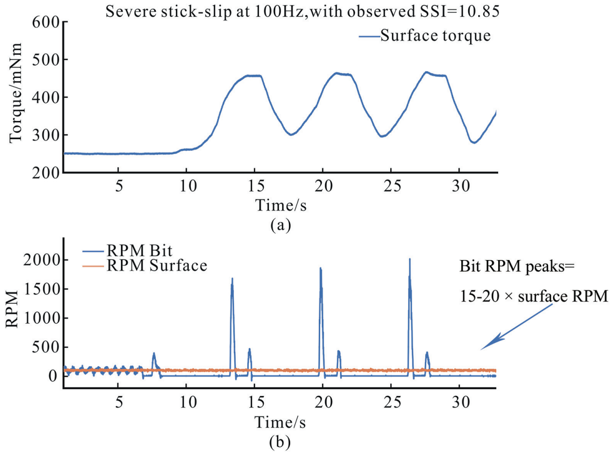


Fig. 13. Surface torque vs time (top), surface and bit RPM vs time (bottom) for test at 100 Hz sampling.

Stick-Slip Index	1 Hz	10 Hz	100 Hz
High Frequency (Mild) Vibrations	0.69	2.57	2.82
Low Frequency (Severe) Vibrations	2.00	8.98	10.85

Fig. 14. Stick-slip index summary for high and low frequency vibrations.

With respect to surface and bit RPM, a few interesting observations can be made for high frequency stick-slip phenomenon. Peaks in bit RPM during stick-slip vibrations is commonly observed. This phenomenon is not caught by the 1 Hz sampling rate test (Fig. 8). Peaks in bit RPM up to 5 times the surface RPM can be observed in both 10 and 100 Hz sampling rate tests (Figs. 9 and 10). RPM peaks at bit represent sudden bit acceleration that has potential to damage downhole tools. Furthermore, negative bit RPM can be observed during bit sticking but only in the 100 Hz sampling test (Fig. 10). In comparison to low frequency bit sticking, the increment in surface torque and bit RPM is not significant and hence can be interpret as mild stick-slip vibrations.

With respect to bit sticking, as observed in Fig. 8, bit RPM does not completely stop in 1 Hz case. However, this does not confirm the absence of bit sticking as bit sticking can be observed in 10 and 100Hz sampling case at approximately 21 s mark. The bit sticking period is observed to be lower than 1 s confirming the characteristic frequency of high frequency stick-slip vibrations at around 1 Hz. The sudden reduction in bit RPM during bit sticking is compensated by an increment in surface torque, as observed in all cases. The increment in surface torque can be seen around 10–15% in the three cases. Interestingly, a similar delay in surface torque response to bit sticking can be observed in all cases which confirms that a similar time is taken for the disturbance wave at the bit to reach the surface. The delay is approximately 2 s and is a function of the drillstring stiffness, length, friction etc.

5.2. Low frequency bit sticking/Severe stick-slip vibration results

Characteristics of low frequency bit sticking include high torque and RPM fluctuations and longer period of bit sticking. As seen in Figs. 11–13, bit sticking of up to 5 s can be observed in all cases. Higher bit sticking period in the stick phase results in a higher energy buildup and consequently, a higher bit acceleration in the slip phase. 1 Hz sampling frequency is not sufficient in estimating vibrations severity as seen in Fig. 11, bit RPM up to 15–20 times the surface RPM can be observed in both 10 and 100Hz sampling tests (Figs. 12 and 13) leading to severe downhole shock and vibrations. Sudden high RPM peaks create a rotational inertia in the drillstring which is compensated by negative rotations. This is only observed in the 100 Hz sampling test, as seen in Fig. 13. Additionally, surface RPM is constant in all three cases proving that it is not an indicator of downhole vibrations.

With respect to torque response, similar torque swings are observed at the surface in all cases of sampling frequency. This proves that high frequency sampling is not required for measuring surface measurements to understand bit sticking severity. Vibrations originating from bit sticking produce waves of disturbance that travel upwards in the drillstring. Unlike high frequency bit sticking, increments of up to 80% can be observed in surface torque response due to severe bit sticking.

6. Conclusions

Low frequency bit sticking is more severe than high frequency bit sticking due to longer bit sticking periods. This can be confirmed by the stick slip index (SSI), an indicator of torsional vibration severity. Maximum SSI is calculated at 2.82 for high frequency bit sticking as compared to 10.85 for low frequency bit sticking. Further comparisons can be observed in Fig. 14.

Higher frequency sampling rates help in improving the detection rate of stick-slip vibration severity. The complete characteristics of stick-slip vibrations including bit sticking, instantaneous RPM peaks and negative bit RPMs were captured only at 100Hz sampling. However, as seen in Fig. 14, a significant increase in stick-slip severity is not observed between 10 Hz and 100 Hz sampling frequency for both mild and severe torsional vibrations. However, the stick slip index increases drastically between 1 Hz and 10 Hz. As a result, a minimum of 10 Hz sampling frequency is recommended as a starting point for better representation of downhole drilling dynamics.

Through experimental testing of up to 100Hz, peaks in bit RPM were observed at 5 times and 15–20 times the surface RPM for high frequency and low frequency stick-slip vibrations respectively.

Amongst surface drilling parameters, top drive torque is a reliable indicator of severe bit sticking phenomenon. Torque increments of up to 15% are observed for high frequency bit sticking and up to 80% for low frequency bit sticking. Interestingly, torque swings due to stick-slip vibrations are independent of the sampling frequency of the surface measurements, as seen in Figs. 8–12. A robust torque severity index is recommended for monitoring stick-slip vibrations.

Declaration of competing interest

No conflict of interest exits in the submission of this manuscript, and the manuscript is approved by all authors for publication.

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Nomenclature

RPM	Revolutions per minute
BHA	Bottom hole assembly
NPT	Non-productive time
ROP	Rate of penetration
WOB	Weight on bit
MWD	Measure while drilling
DAQ	Data acquisition
ADC	Analog-to-digital converter
SSI	Stick-slip index

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