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Investigating the Mechanisms, Impact, and Mitigation of Stick-Slip Vibrations in Drilling Operations

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Abstract

Stick-slip vibrations present enormous challenges to the operational efficiency of drilling operations and affect the integrity of the equipment. In light of this fact, the present study is an effort to unveil the underpinning mechanisms, impact assessment, and possible mitigation strategies. The study applies an integrated approach that merges theoretical insights with practical solutions and uses numerical simulation through the DrillScan simulator to validate and refine the stick-slip vibrations. The numerical simulation serves as a powerful tool, enabling a detailed examination of the dynamics and behavior of the drillstring under varying conditions. The study explores the improved prediction accuracy of the stick-slip by use of modern numerical modeling as an understanding aid to aspects of various operations. The paper will consider, in broader detail, the stick-slip implications on drilling, such as wear and tear of equipment, increased time for drilling, and such related issues, inclusive of the potential for damaging the wellbore. The research identifies several approaches that might be applied in devising effective strategies of mitigation, from operational adjustment to technological solutions that might be applied in the reduction of stick-slip vibrations. The anticipated findings are expected to provide valuable insights to the petroleum industry, facilitating the development of targeted measures aimed at mitigating the adverse effects of stick-slip vibrations and ultimately enhancing overall drilling performance.

1.0 Introduction

Mechanical systems characterized by mass and elasticity inherently possess multiple natural frequencies of free vibration (Finnie and Bailey 1960). Each of these frequencies corresponds to a specific natural mode of vibration, whether it is torsional, axial, or lateral. In the case of a mechanical system, such as a drill string, subjected to varying forces with frequencies in close proximity to the system's natural frequencies which can result in the vibrations that can reach exceptionally high amplitudes. In scenarios where the excitation frequency precisely matches a natural frequency, the amplitude of vibration becomes limited primarily by the damping capacity within the system, which dictates the dissipation of energy. In situations where damping falls short of what is required, the consequences can be severe, potentially leading to system failure (Finnie and Bailey 1960).

Torsional vibrations, often referred to as "stick-slip" vibrations, are a significant challenge in the context of drilling operations in the oil and gas industry. These vibrations have a detrimental impact on drilling performance, resulting in reduced tool longevity and diminished productivity. Mitigating stick-slip vibrations involves employing various techniques, including the manipulation of operational parameters and the utilization of control tools. Despite substantial advancements in addressing this issue, effectively suppressing stick-slip vibrations continues to be a formidable obstacle within the drilling sector (Zhu, Tang, and Yang 2014).

Within the rotary drilling process, the means by which the drill string undergoes rotation is either through a top drive system or a rotary table and is typically set to a consistent speed. Nonetheless, the rotational velocity experienced by the lower end of the drill string, namely the drill bit, displays variations due to oscillations resulting from the relatively low torsional rigidity of the drilling pipes. The amplitude of these oscillations is contingent upon three key factors: the characteristics of the surface-based drive system, the frictional forces prevailing between the wellbore and the drill string, and the dynamic interactions that transpire between the drill bit and the rock formation being drilled (Robnett et al. 1999).

To understand, control, and mitigate stick-slip vibration field experiment which examines the drill string under vibration, the efficiency of the downhole data transmission and the evaluation of the performance of the bit has significantly helped in investigating the drilling process. Unavoidable drilling dynamics such as vibrations and shocks occur in circumstances where the drilling bits exhibit high aggressiveness during drilling operations in extended drill strings, low-drillability rock formations, and other similar conditions, which can have a detrimental effects on drilling tools such as drill collars, drill pipes, and drill bits(Abbassian and Dunayevsky 1998; Rector and Marion 1991). Logging and monitoring tools may be susceptible to extensive harm from vibrations, as indicated by (Reckmann et al. 2010). Moreover, these vibrations and shocks can have a considerable effect on the integrity of the wellbore, leading to increased non-productive time (NPT) and lower rate of penetration(Macpherson, Mason, and Kingman 1993). Different models have been used for the study of torsional vibration in the drill string. (Brett 1992) explains that stick-slip vibrations manifest as a consequence of torsional vibrations within the drill string, which occur when the static friction coefficient surpasses the dynamic friction coefficient. The manifestation of stick-slip is predominantly characterized by the rapid and erratic motion of the drilling apparatus. This may result in costly outcomes, including harm to drilling equipment, diminished drilling productivity, and heightened operational risks(Zakuan et al. 2011; Riane et al. 2022).

Scaled-down laboratory trials offer an effective means of evaluation due to their capacity to replicate testing conditions within a controlled and low-risk setting. Furthermore, the straightforward setup and operation of these scaled laboratory experiments empower industry professionals and academic institutions to generate conclusive research findings on drilling procedures. This is particularly applicable to the promising field of drilling automation (Sharma, Srivastava, and Teodoriu 2020).

In the ongoing shift towards automation within the drilling sector, downscaled experimental test setups offer a secure platform for the systematic deployment of automation methodologies. Endsley & Kaber (1999) presents a scale of automation levels from 1 to 10, where 1 represents manual control with all tasks performed by humans, and 10 indicates full automation with all tasks performed by computers. The tasks were categorized into monitoring, generating, selecting, and implementing. As the level of automation increases, the involvement of computers increases while human involvement decreases. In the middle levels (2 to 8), there is a mix of human and computer involvement, with different combinations depending on the task and the level of automation. At the highest levels (9 and 10), computers take over all tasks, with level 9 retaining human oversight in the monitoring process, as depicted in Table 1.

Moreover, a critical examination of an experimental configuration, which incorporates a certain degree of automation, has been conducted to assess the analysis of drill string vibrations as outlined by Aditya and Teodoriu (Sharma, Srivastava, and Teodoriu 2020).

Table 1. Levels of automation (“Level of Automation Effects on Performance, Situation Awareness and Workload in a Dynamic Control Task,” n.d.)

	Level of Automation	**Monitoring**	**Generating**	**Selecting**	**Implementing**
1	Manuel Control	Human	Human	Human	Human
2	Action Support	Human/Computer	Human	Human	Human/Computer
3	Batch Processing	Human/Computer	Human	Human	Computer
4	Shared Control	Human/Computer	Human/Computer	Human	Human/Computer
5	Decision Support	Human/Computer	Human/Computer	Human	Computer
6	Blended Decision Control	Human/Computer	Human/Computer	Human/Computer	Computer
7	Rigid System	Human/Computer	Computer	Human	Computer
8	Automated Decision Making	Human/Computer	Human/Computer	Computer	Computer
9	Supervisory Control	Human/Computer	Computer	Computer	Computer
10	Full Automation	Computer	Computer	Computer	Computer

The primary objective of this paper is to introduce an elevated level of automation and outline the development of a laboratory-scale experimental testing apparatus designed to investigate drill string vibrations, with a specific emphasis on torsional vibrations. The paper further expounds upon the instrumentation process, offering a comprehensive integration of mechanical and electrical components within the testing apparatus. It also provides insights into the programming intricacies and the development of a human-machine interface.

2.0 Stick-Slip Mechanism

A primary goal of drilling operations is to drill wells safely and in a cost-effective manner. Mensa-Wilmot et al. (2010) highlight that enhancing drilling efficiency is crucial, and one of the key performance qualifiers (PQ) that must be managed is drilling vibration (Mensa-Wilmot et al. 2010). Controlling this aspect is essential for improving overall operational performance. Vibrations in the drill string present significant challenges in the process of drilling for hydrocarbon exploration and extraction. These vibrations manifest in three primary forms: axial, torsional, and lateral, each leading to distinct issues such as bit bounce, stick-slip, and bit whirl, respectively (Sharma et al. 2023). This study specifically addresses the stick-slip phenomenon, characterized by a cyclical pattern of the drill bit halting (sticking phase) and then suddenly rotating at speeds exceeding those at the surface (slipping phase). This creates a problem in which the rotation difference will start to exist between constant rotation induced by the top drive system or rotary table at the top with the fluctuating bit speeds due to drill-string oscillations from low torsional rigidity at the bottom (Shen et al. 2017; Sharma et al. 2023). Stick-slip occurs when the dynamic friction coefficient drops significantly below the static friction coefficient (Brett 1992). The oscillation periods of this vibration typically span from 2-10 seconds (Jansen and van den Steen 1995). In the stick phase, the bottom hole assembly (BHA) periodically ceases rotation, leading to torque accumulation. This stored energy is then abruptly released during the slip phase. Figure 1 presents a graph illustrating surface and bottom hole revolutions per minute (RPM) from a field experiment, clearly depicting stick-slip occurrence. In instances of intense stick-slip events, it has been documented that the RPM at the bottom hole can surge to levels 10 to 15 times greater than those measured at the surface during the slip phase (Cunningham 1968; Dufeyte and Henneuse 1991).

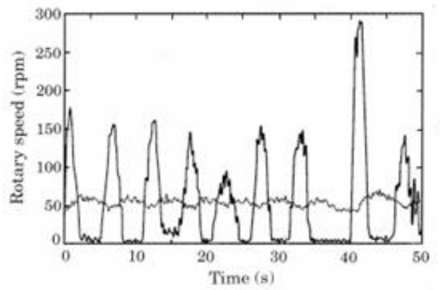


Figure 1. Stick-slip oscillation (Jansen and van den Steen 1995)

3.0 Influencing Factors on Stick-Slip Vibration

Grasping the variables that influence stick-slip occurrences is crucial for applying preventative measures against this phenomenon. Figure 2 highlights three significant input parameters affecting the output of the drilling process.

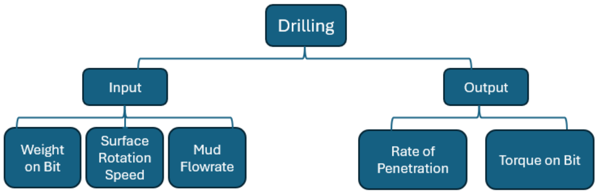


Figure 2. Input and Output drilling parameters.

The inputs include Weight on Bit (WOB), which controls the force applied to the drill bit; Surface Rotation Speed, determining how fast the drill bit turns; and Mud Flowrate, which manages the volume of drilling fluid for various functions like controlling well pressure and removing drill cuttings. These parameters are critical levers that drilling operators can adjust to influence the drilling efficiency. On the output side of the process is the Rate of Penetration (ROP), the metric for how quickly the drill bit penetrates the subsurface. It is a direct reflection of the drilling operation's effectiveness, relying heavily on the careful balance and optimization of the input parameters. The goal in managing these inputs is to achieve the highest possible rate of penetration (ROP) while ensuring the safety and integrity of the entire drilling operation (Ejike et al. 2024).

Several factors need to be considered to control stick-slip vibration. Figure 3 represents the interrelated factors that contribute to stick-slip vibration in drilling operations. All these parameters need to be considered holistically to have better vibration control.

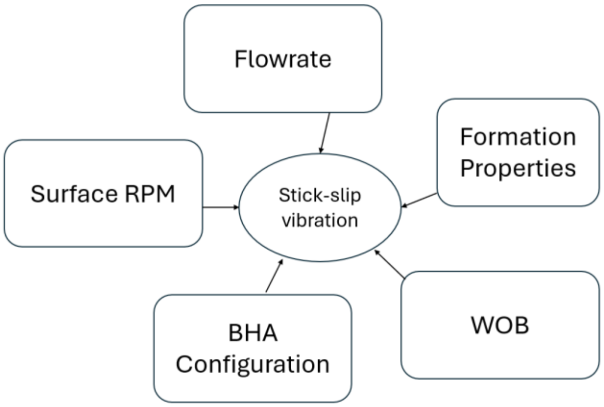


Figure 3. Some factors impacting Stick-slip vibration.

To have a deeper understanding of the underlying reason behind the stick/slip vibration, some assumptions have been formulated over the course of the last three decades. (Kyllingstad and Halsey 1988) established that stick/slip vibration during drilling can be linked to fluctuations in downhole friction torque. This torque arises from the static-to-dynamic transition in friction between the drill-string and the wellbore, or from the interaction between the bit and the rock. Brett (1992) posited that the primary reason for the stick/slip phenomenon in a PDC bit is the decrease in torque when the rotational speed is increased. Fear et al. (1997) substantiated this presumption by a statistical examination of 300 units of data. The study by (Gao et al. 2022) highlights the importance of surface deformations caused by wear on the bit in determining stick-slip friction and concluded that by promptly reducing the high-frequency stick-slip vibrations, one can effectively prevent the occurrence of other forms of vibrations as well. Stick-slip vibrations can occur due to dynamic load fluctuations caused by sudden changes in the weight applied to the drill bit or WOB. (Tang et al. 2017) employed a lumped drilling system torsional pendulum model to examine the weight on bit (WOB) in torsional stick-slip vibration. It was shown that when the weight on bit (WOB) reaches a specific threshold, the behavior of the drill bit may transition from a consistent motion to a stick-slip vibration due to an elevated WOB.

4.0 Mitigation Strategies

Numerous strategies for mitigating stick/slip have been documented in the literature. These strategies can be categorized into three main groups: optimization of drilling parameters, optimization of bottomhole assembly (BHA) and drillstring design, and optimization of bit design. (Kyllingstad and Halsey 1988) introduced a feedback mechanism aimed at regulating the rotational speed of the top drive to prevent bit stick/slip occurrences. Their research indicated that reducing downhole static friction or adjusting the rotary speed could effectively diminish or eliminate stick/slip vibrations. This innovative approach has since been incorporated in modern drilling rigs, with its efficacy in stick/slip mitigation being highlighted in studies by (Runia, Dwars, and Stulemeijer 2013; Dwars 2015; Dao, Menand, and Isbell 2019). Studies by Bailey and Remmert (2010) as well as Bailey et al. (2018) demonstrated that stick/slip vibrations induced by the BHA can be alleviated through optimization of BHA design, such as the strategic placement of roller reamers and stabilizers. Additionally, Davis et al. (2012) observed that increasing the torsional stiffness of the drill string can also contribute to reducing stick/slip vibrations.

The study also focuses on using an experimental setup that mimics the dynamic of a drill string in a vertical well to investigate, analyze and control stick-slip vibrations. DrillScan, a drilling simulator software developed by Helmerich and Payne Inc., was also used to validate the stick-slip behavior of the experimental setup.

5.0 Experimental Approach

The experimental laboratory test rigs used for this study was designed by (Sharma, Srivastava, and Teodoriu 2020) which provided a new dimension to the integration of mechanical and electrical components for a proposed approach set by (Srivastava and Teodoriu 2019) for the experimental design of laboratory test rigs for comprehensive analysis which aided in the existing design of the rig. The experimental setup used in this study is illustrated in Figure 4.

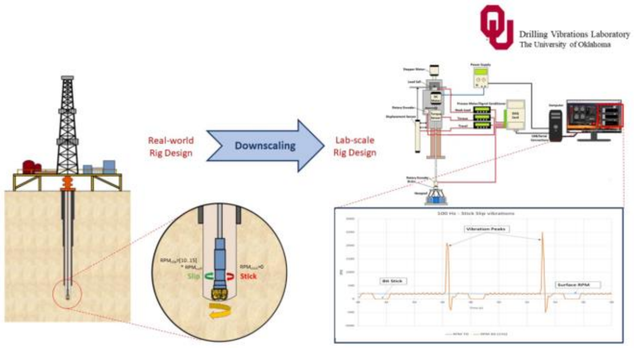


Figure 4. Experimental Configuration (Sharma, Srivastava, and Teodoriu 2020)

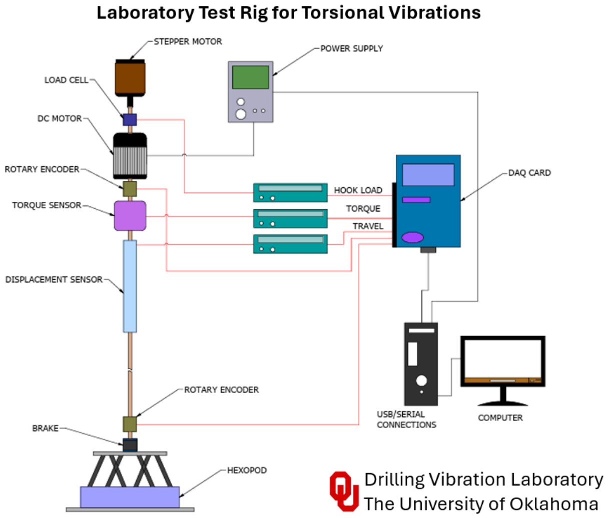


Figure 5. Schematic of Experimental Setup

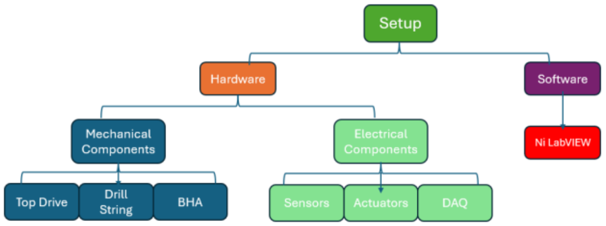


Figure 6. Components of Experimental Setup

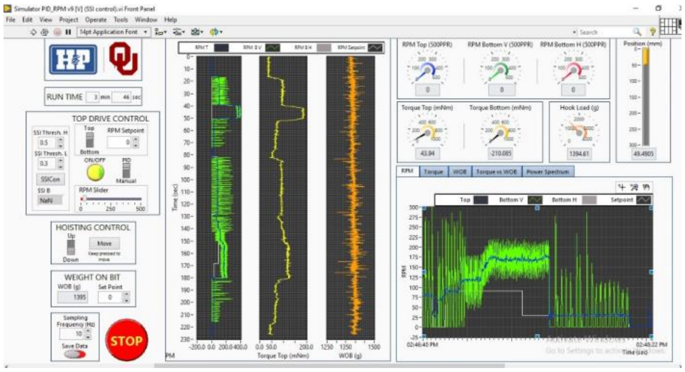
The top drive of the experimental setup consists of an 18V DC motor for providing rotational energy to the drill string and a stepper motor with a lead screw mechanism for hoisting and controlling weight on bit (WOB). The DC motor provides a constant voltage for smooth torque output. The experimental drill string is composed of a slender PVC pipe with an Outer Diameter (OD) of 4 mm and a length of 49 feet, establishing a downscaling ratio of 1:30. PVC was selected over materials such as aluminum or steel for the construction of the drill pipe because of its low torsional rigidity, which facilitates the generation of torsional vibrations with a specific amount of downhole torque applied in the experimental setup.

To initiate torsional vibrations in the drill string, torque must be produced at the drill bit. This torque can originate from either the actual drilling process involving a rock sample or a specialized braking system that simulates the torque applied to the bit. Considering the necessity for consistent and reproducible results in the experimental setup, the braking system approach was used. The testing apparatus incorporated an advanced hexapod braking system capable of multidirectional movement across six axes, even while applying braking forces. This sophisticated system employed an electromagnetic brake to exert the necessary torque on the bottom hole assembly. Additionally, it was integrated with a rotary encoder, which was instrumental in measuring the exact angular displacement during the experimental procedure, ensuring high precision in monitoring the assembly's movements.

The system utilized a multi-functional 16-bit data acquisition device (DAQ) that could sample at rates up to 250 kHz, capturing analog voltage inputs and digital signals from rotary encoders. The analog sensors' dc voltage outputs and the digital data were processed through LabVIEW software. An Arduino Mega was also employed for its numerous input/output capabilities, mainly to process digital signals from the rotary encoders into RPM and directional data, which was then transmitted to LabVIEW via serial communication. However, due to its limited processing speed, the Arduino Mega's sampling frequency was constrained, which affected the reliability of data at higher frequencies during the testing phase of the experimental setup.

Signal conditioning was necessary for the strain gauge sensors that produced millivolt signals. Signal conditioners within process meters adapted these signals to a readable range for the DAQ, providing real-time measurements on displays. This setup allowed for accurate scaling and displaying of weight on bit (WOB), torque, and displacement data before it was read by the DAQ.

LabVIEW, a graphical programming platform, was central to the system design, enabling data acquisition, control automation, and integration with various data acquisition platforms. It was used to program, control the setup, process data, and develop the human-machine interface (HMI), displaying process parameters on the HMI and providing control over the system's actuators, such as the top drive motor and the hoisting stepper motor as shown in Figure 7.



RUN TIME 3 min 46 sec

SSI Thresh. H 0.5

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RPM Setpoint 0

WOB (g) 1395

Set Point 0

Sampling Frequency (Hz) 10

Save Data

RPM Top (500PPR) 0

RPM Bottom V (500PPR) 0

RPM Bottom H (500PPR) 0

Torque Top (mNm) 43.94

Torque Bottom (mNm) -210.085

Hook Load (g) 1394.61

Position (mm) 49.4905

Figure 7. Human Machine Interface for control and monitoring of experimental setup (after Aditya, 2023)

6.0 Experimental Results and Discussions

The experimental setup is to replicate real-time stick-slip vibration scenarios, a critical phenomenon commonly encountered during drilling operations. This forms the foundation of the results and discussion in this chapter, where we systematically present the data collected from the experimental setup. The nuanced behaviors captured during these simulations offer a rich dataset for analysis and subsequent scrutiny. To further improve the credibility of our findings, validation is performed using Drillscan, a sophisticated software tool specifically designed for drilling simulations. Through this validation process, we were able to cross-verify the experimental data against the simulated models, ensuring that our interpretations are not only grounded in empirical evidence but also reinforced by an advanced computational prediction. The ensuing dialogue intertwines the empirical results with theoretical insights, providing a well-grounded understanding of the stick-slip dynamics. The experimental test and results presented in this study focus on the effect of rotation speed on stick-slip vibration and the impact of “stick” and “slip” behavior in the experimental setup.

Figure 8. illustrates the rotational speed (RPM) of a drill string over time, highlighting the phenomenon of stick-slip vibration setup. Stick-slip is characterized by a cycle of motion where the drill string alternately sticks (stops rotating) and then slips (rotates suddenly), which is a common issue in drilling that can lead to equipment damage and inefficient drilling.

At a lower RPM (noted as 50 and 100 RPM), the system experiences severe stick-slip events. This is indicated by relatively small changes of the red line (RPM at the top), which shows the top RPM dropping to zero represented in green line (RPM at bottom), signifying that the drill string has stopped rotating (stick). Subsequently, the RPM oscillates abruptly above the set RPM, as shown by the spikes in the graph, representing the slip phase where the accumulated energy is released, causing the string to rotate rapidly.

As the graph progresses to show higher RPMs (450 RPM), marked by the green line for the bottom RPM, the torsional oscillations become more uniform, indicating that the system may be transitioning out of the severe stick-slip regime into a more stable rotational behavior with controlled oscillations around a set RPM value shown. This phase is critical for drilling operations as it may represent a more manageable state, reducing the risks associated with stick-slip vibrations.

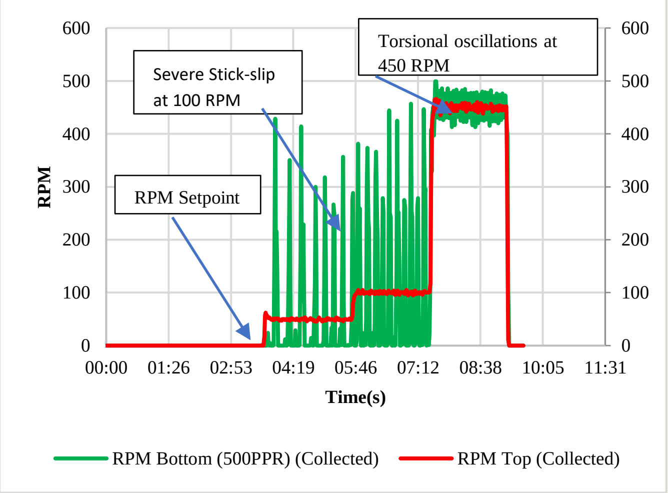

Figure 8. Results from Experimental Setup

7.0 Modelling and Validation Using DrillScan

To validate and ensure the accuracy and reliability of our experimental findings, the validation of experimental results was conducted with the Drillscan software. This phase was pivotal, serving as a bridge between theoretical models and real-time applicability. Drillscan is not just a tool but a gateway to a comprehensive understanding of drilling dynamics, offering a platform for simulating a myriad of drilling scenarios with unparalleled precision. Through the creation of a highly accurate drill-string model, which replicates the physical attributes and dimensions of our experimental setup, a series of simulations were conducted. These simulations were comprehensively tailored by varying RPM to mirror the complexities of actual drilling operations. The convergence of our simulated results with those obtained from the physical experimental setup shows the reliability of our testing setup.

This section will discuss the nuances of our validation efforts, underscoring the alignment between our simulated outcomes and experimental data collected, thereby reinforcing the credibility of our research findings. The process began with the construction of a model based on an experimental setup and systematically adjusting key variables to mimic stick-slip vibration within the drill string. This setup paved the way for a sequence of simulation runs aimed at analyzing the stick-slip behavior inherent to the setup. The overarching goal was to dissect the effects of different parameters on stick-slip events. To achieve this, the simulator was calibrated using data derived from the experimental phase, where variations in rotation speed served as a primary method to mitigate stick-slip incidents. This strategy provided insights into the behavior of stick-slip phenomena as a function of increased rotational speed. Throughout this validation process, other factors like Weight on Bit (WOB) and Torque on bit (TOB) have not been discussed in this analysis.

Figure 9. Validation of the experimental result through DrillScan software

The graph in Figure 9 shows RPM evolution over time for a drilling operation as simulated by Drillscan. Initially, there is a significant variation in RPM, which is indicative of the stick-slip effect, where the rotational speed of the drill string oscillates between high and low extremes. This is observable through the repeated spikes and drops in RPM, which correspond to the drill string sticking and then suddenly accelerating or slipping.

Around the 200-second mark, the RPM rapidly increases and then stabilizes at a high level. Following this increase, the previously observed stick-slip pattern vanishes, and the RPM maintains a relatively steady state. This stabilization indicates that increasing the RPM has effectively neutralized the stick-slip effect.

The graph illustrates that a rise in RPM can smooth out the drilling operation, eliminating the oscillatory pattern that characterizes stick-slip. This supports the understanding that higher rotational speeds can help maintain consistent drilling and avoid the torsional oscillations associated with stick-slip, which is a common strategy employed in drilling to prevent such adverse vibration effects.

8.0 Conclusions

Through extensive experimentation and analysis, it has been determined that the regulation of rotation speed is a crucial parameter to be taken into account in the efforts to reduce stick-slip occurrences. The experimental methodology played a significant role in gaining insights into the factors contributing to stick-slip vibrations. This application of an experimental setup not only validates the theoretical predictions but also provides an understanding of the drilling dynamics. Contributing to the field of drilling research and development, this study also emphasizes the potential of experimental approaches in tandem with simulation tools like DrillScan to present valuable solutions. These integrative techniques provide a replicable and scalable way to test and refine drilling operations, bringing the industry closer to more automated and optimized processes.

In anticipation of the future, it is recommended to construct more robust setups capable of facilitating a wider array of operational variables. Subsequent research endeavors need to concentrate on the incorporation of real-time monitoring mechanisms and the utilization of machine learning algorithms for the prediction and mitigation of stick-slip occurrences prior to their escalation. Also delving deeper into the composition of drilling strings and the influence of environmental factors may unveil additional strategies for mitigation.

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Nomenclature

WOB	Weight-on-bit
RPM	Revolutions per minute
TOB	Torque on Bit
DAQ	Data Acquisition Device
HMI	Human Machine Interface

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