PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Optimization of Drilling Parameter to Minimize Torsional Vibrations in Geothermal Wells

Chinedu Ejike, Abid Khizar and Catalin Teodoriu

Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma, OK, 73019, United States

cteodoriu@ou.edu

Keywords: stick slip, aggressiveness, weight, torque, rotation speed

ABSTRACT

Geothermal drilling poses significant challenges due to high temperatures, harder rock formations, and complex geological conditions, which intensify torsional vibrations in the drill string. These vibrations adversely impact drilling efficiency, increase operating costs, and reduce equipment lifespan. This study employed numerical simulations to optimize drilling parameters, specifically focusing on mitigating torsional vibrations in geothermal wells. Key parameters such as weight on bit (WOB) were systematically varied to analyze their influence on vibration behavior. The objectives were to identify the factors most critical to torsional vibration control, develop optimization strategies, and provide best practices for geothermal drilling. A comparative analysis between geothermal and conventional wells highlighted the challenging conditions in geothermal environments, which lead to prolonged sticking phases and more severe torsional oscillations. Analysis was done to evaluate the effectiveness of different WOB values in reducing stick-slip tendencies, with findings showing that lowering WOB minimized sticking phases and improved synchronization with the top drive rotation speed. The results demonstrate that torsional vibrations are inherently more pronounced in geothermal wells due to their geological and thermal properties.

1. INTRODUCTION

Geothermal energy represents a promising, sustainable solution to global energy needs, with the potential to provide a constant and clean energy source [1]. However, the technical challenges associated with geothermal drilling, particularly in hard rock formations and at high temperatures, pose significant operational and economic obstacles [2 – 3]. One of the critical issues in geothermal drilling is the phenomenon of torsional vibrations, which lead to severe fluctuations in the bit rotational speed [4 – 5]. These vibrations, often manifesting as stick-slip can drastically reduce drilling efficiency, increase wear on drilling components [6 – 8], and raise the risk of equipment failure [9 – 12]. Optimizing drilling operations to control these vibrations is essential to ensure efficient and cost-effective geothermal well development.

Geothermal wells tend to experience more severe vibrations than conventional oil and gas wells due to several unique operational factors [3]. Geothermal reservoirs typically operate at much higher temperatures than oil and gas reservoirs, causing thermal expansion and material degradation that affect the performance and durability of drilling tools and fluids. Additionally, geothermal drilling often encounters hard, abrasive igneous and metamorphic rock formations, which demand higher energy at the drill bit and increase the likelihood of torsional vibrations. Drilling through these tough formations requires higher weight on bit (WOB) and unconventional parameter settings, which amplify torque variations and mechanical stress on the drill string. The combination of high weight on bit (WOB), specialized high-temperature drilling fluids, and unconventional parameter settings creates an environment highly prone to dynamic instability and severe vibrational effects. Torsional vibrations are influenced by several drilling parameters, such as the rotational speed (RPM), WOB, torque, and mud properties [4]. In recent years, research in vibration control has emphasized the importance of tuning these parameters to stabilize drill string dynamics and improve performance [5].

Several works have been done on torsional vibrations. Discrete models have also been applied in analyzing the interaction between torsional and axial vibrations with specific reference to the effect of bit rock interaction on drill stem vibrations. The contributions in works by [13-17] affirm the existence of stick-slip instabilities in these models by assuming a constant friction coefficient. However, the approach by Richard et al. [14] for axial and torsional damping is not considered. Besselink et al. [18] modified the model equations of Richard et al. [14] by incorporating damping into the axial motion and taking into account the axial stiffness of the drill pipe but neglecting torsional damping. It was shown from this work that stick-slip arises from a coupled delay time, friction, and cutting effects at the bit. An active control system of the rotational speed is proposed as one of the ways to mitigate severe stick-slip problems [15,17]. Two different Rate of Penetration (ROP) models, linear and nonlinear, were considered by Sharma et al. [19] to evaluate the influence of ROP on bit-rock interaction and general drilling vibrations. Dunayevsky et al. [20] analyzed drill string dynamics for a wide range of drilling parameters using a finite element model of continuous wall contact. Having a detailed model of parametric resonance, they could detect failure modes but did not capture failure's time-dependent behavior and excluded whirl and stick-slip effects. The different rock types were analyzed with laboratory and field experiments by Dykstra et al. [21], who gave suggestions for the reduction of downhole vibrations caused by operational deficiencies. Kriesels et al. [22] introduced the Soft Torque Rotary System (STRS) as an alternative means of attenuating torsional vibrations, especially stick-slip problems. After the introduction of the STRS, penetration rates and bit life both improved. The use of vibration analysis software in the design of Bottom Hole Assemblies, in combination with more frequent surveys of the drillstring components, further improved the drilling performance. According to Leine et al. [23], Finite Element Models provide valuable quantitative insights into the dynamics of the drill string. They further noted that with Finite Element Models, there arise very complex problems that are, however, highly nonlinear with large displacements and consequently difficult to investigate for certain vibration behavior entailed during drilling operations.

However, most of the studies were conducted on oil and gas wells, where temperatures and, particularly, the rock formation are vastly different from those in the geothermal environment. This gap indicates the need for special research in the development of methodologies to optimize the process of drilling with the parameters aimed at geothermal wells, considering the specific problems of their exploration. This study is aimed at finding how to set various drilling parameters to minimize torsional vibrations for geothermal wells. In this work, an attempt will be made to identify the settings of the parameters for stability and reduced intensity of vibration through numerical simulations. The ultimate goal of such findings is to help the geothermal industry surmount all problems relating to the drilling process so that geothermal energy is developed as a competitive source of energy. The optimization strategies developed herein could also give insight into improving drilling execution in other unconventional high-temperature settings.

2. NUMERICAL SIMULATIONS

A numerical simulator was used to model an upscaled drill string at a bit depth of 446.1 m. The string configuration included components such as a polycrystalline diamond compact (PDC) bit, near-bit stabilizers (NBS), string drill collars (SDC), vibration generating subs (VGS), drill collars (DC), stabilizers (SS), measurement while drilling (MWD), heavyweight drill pipe (HWDP), and drill pipe (DP). Table 1 provides a detailed illustration of the drill string configuration. The time-domain analysis module of the simulator was applied in this study to assess the effects of varying WOB while maintaining other critical parameters such as torque, RPM, and mud flow rate constant.

Bit aggressiveness is a crucial factor in the analysis of torsional stick-slip behavior, particularly in geothermal formations. Aggressiveness refers to the bit's ability to engage and cut through rock under specific operational conditions. Geothermal wells typically exhibit a bit higher aggressiveness than conventional formations due to increased tectonic activity, harder rock formations, and elevated temperatures. These factors intensify the torsional vibrations experienced during drilling operations. This concept formed the basis of the simulation, where specific values were assigned to represent the bit aggressiveness in both conventional and geothermal wells. A value of 50 kgf·m/tf was assigned for conventional wells, while a 100 kgf·m/tf was used for geothermal wells to account for the harder rock properties associated with geothermal drilling. These values are supported by the increased cutting force and torque requirements typical in geothermal environments. Table 2 summarizes the input parameters for the four simulation runs. The analysis compared the bit RPM for both conventional and geothermal scenarios, demonstrating the significant impact of bit aggressiveness on torsional stick-slip tendencies.

Table 1 Drill string configuration

Type	Length	OD	ID	Gauge	Total length	Mass	Total mass	Linear mass	OD tool joint
	(m)	(inch)	(inch)	(inch)	(m)	(kg)	(kg)	(kg/m)	(inch)
PDC	0.45	-	-	5 5/8	0.45	28.16	28.16	62.59	-
NBS	1.6	4 1/2	2 1/8	5 5/8	2.05	100.14	128.3	62.59	-
SDC	1.75	4 1/2	2 1/8	-	3.8	109.53	237.83	62.59	-
VGS	3	4 1/2	2 1/8	VARIABLE	6.8	187.76	425.58	62.59	-
SDC	3.7	4 1/2	2 1/8	-	10.5	231.57	657.15	62.59	-
DC	9	4 1/2	2 1/8	-	19.5	563.27	1220.42	62.59	-
SS	1.6	4 1/2	2 1/8	5 5/8	21.1	100.14	1320.56	62.59	-
MWD	10	4 1/2	2 1/8	-	31.1	625.86	1946.42	62.59	-
DC x 6	54	4 1/2	2 1/8	-	85.1	3379.64	5326.06	62.59	-
HWDP x 10	95	3 1/2	2 1/16	-	180.1	3170.08	8496.14	33.37	4 1/2
DP x 28	266	3 1/2	2 5/8	-	446.1	6416.2	14912.34	24.12	5

Table 2 Input parameters

	WOB (tf)	Mud density (SG)	Time (sec)	Aggressiveness (kgf.m/tf)	
				Conventional	Geothermal
1	200	1.2	30	50	100
2	150				
3	100				
4	50				

3. RESULTS AND DISCUSSIONS

The bit RPM in both geothermal and conventional wells was monitored and compared with the keyed top RPM to assess the impact of WOB on stick slip torsional vibrations.

In the first case, with a WOB of 200 tf, Figure 1 illustrates that the bit experiences sticking from the onset. Sticking occurs when the bit becomes stationary and does not rotate at depth due to high resistance from the formation. The duration of the sticking phase is significantly longer in the geothermal well compared to the conventional well, emphasizing the more challenging conditions in geothermal formations. After approximately 30 sec, the bit in the conventional well overcomes sticking and begins to experience torsional oscillations, eventually synchronizing with the top RPM. In contrast, the bit in the geothermal well overcomes its sticking phase after 45 sec, reflecting its greater resistance to rotation under the same WOB.

When the WOB was reduced to 150 tf, Figure 2 shows the corresponding behavior of the bit. At this point, the duration of the sticking phase decreased in both well types. In the conventional well, the sticking phase is significantly shorter, while prolonged sticking is still evident in the geothermal well. Once the system overcomes sticking, the bit mimics the top RPM, but the geothermal well lags due to its harsher drilling conditions.

Further reducing the WOB to 100 tf, as shown in Figure 3, results in an even shorter sticking phase. The bit in the conventional well overcomes sticking after 22 sec, while the bit in the geothermal well takes 30 sec to reach a similar state. This demonstrates the direct relationship between reduced WOB and decreased sticking duration.

Finally, with the WOB reduced to 50 tf (Figure 4), both well types drastically minimize the sticking phases. However, the geothermal well continues to exhibit slightly prolonged sticking compared to the conventional well, showing the need for careful parameter tuning in challenging geothermal environments.

While increasing WOB can improve the ROP, these results highlight the importance of optimizing WOB to balance drilling efficiency and minimize long episodes of torsional vibrations, particularly in geothermal wells. Excessive WOB in geothermal formations can exacerbate torsional stick-slip and negatively impact drilling performance, making fine-tuning an essential aspect of effective drilling operations.

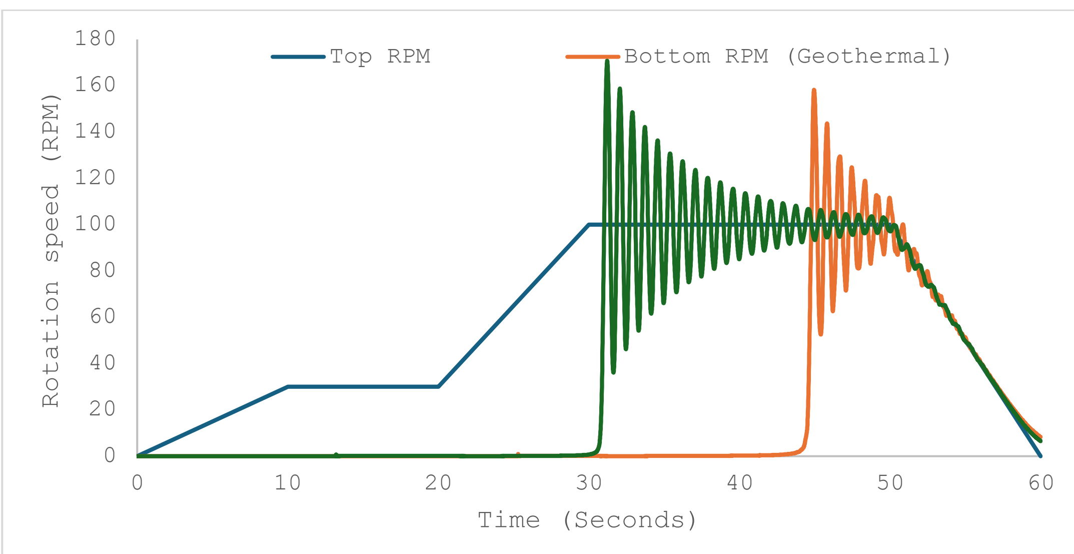

Figure 1 Bit behavior at WOB of 200 tf

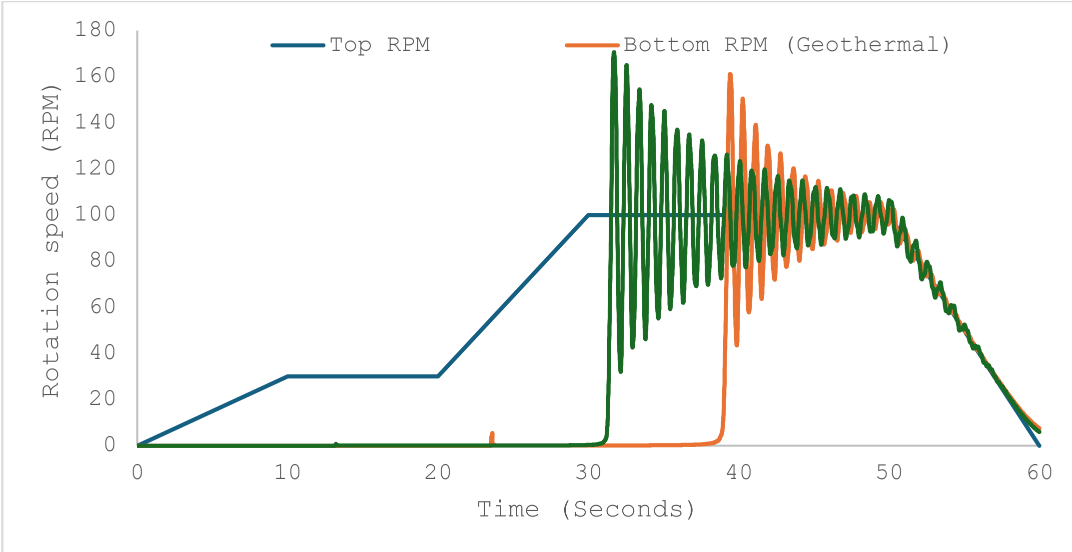

Figure 2 Bit behavior at WOB of 150 tf

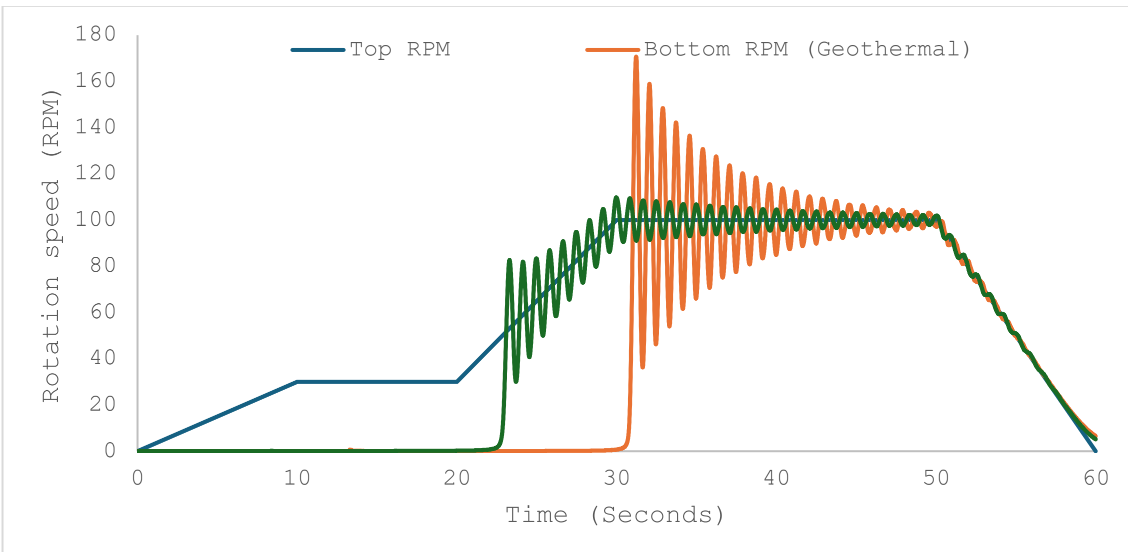

Figure 3 Bit behavior at WOB of 100 tf

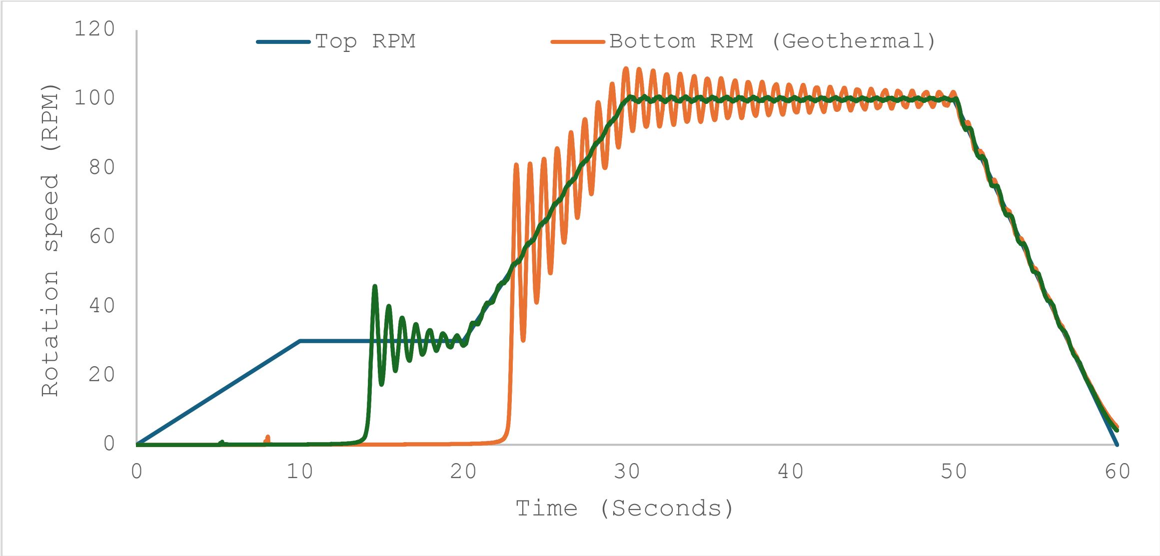

Figure 4 Bit behavior at WOB of 50 tf

4. CONCLUSIONS

This study analyzed the optimization of drilling parameters, focusing on WOB, to minimize torsional vibrations in geothermal wells. Using a numerical simulator, a drill string at a bit depth of 446.1 m was modeled and compared for geothermal and conventional wells under varying WOB conditions. The findings show the critical role of WOB in mitigating torsional stick-slip behavior, especially in the challenging environment of geothermal formations. The results reveal that higher WOB values lead to prolonged sticking phases, particularly in geothermal wells. However, increased WOB is usually required to drill to harder formations. The prolonged sticking observed in geothermal wells is attributed to the harsher formation conditions, illustrated by the high aggressivity. Progressive reduction of the WOB showed a consistent decrease in the duration of the sticking phase. Lowering the WOB allows the bit to overcome sticking faster and synchronize more effectively with the top RPM. However, even at reduced WOB, the geothermal wells continued to exhibit longer sticking durations, reflecting their inherently greater resistance to torsional motion.

This paper may also suggest a different way to start the rotation process using smarter top drives that can ramp up the ROM in a different way.

Our findings may suggest that to avoid stick-slip situations in deep geothermal wells, they may require bits with less aggressiveness but high ROP.

ACKNOWLEDGEMENT

The authors would like to thank Helmerich and Payne INC. for their support in building and maintaining the OU drilling vibration laboratories, as well as for their priceless support for the WellScan software package. We also would like to thank the OU Drilling Vibration Laboratory at the University of Oklahoma.

ACRONYMS

WOB – Weight on bit

RPM – Rotational speed

ROP – Rate of penetration

STRS – Soft torque rotary system

PDC – Polycrystalline diamond compact

NBS – Near bit stabilizers

SDC – String drill collars

VGS – Vibrations generating subs

DC – Drill collars

SS – Stabilizers

MWD – Measurement while drilling

HWDP – Heavy weight drill pipe

DP – Drill pipe

REFERENCES

[1] Raymond, D., Knudsen, S., Blankenship, D., Bjornstad, S., Barbour, J., and Schen, A. "PDC Bits Outperform Conventional Bit in Geothermal Drilling Project." GRC Resources Council Transactions, vol. 6, 2012, pp. 307-315.

[2] Akhtarmanesh, S., Atashnezhad, A., Hareland, G., and Al Dushaishi, M. "ROP Model for PDC Bits in Geothermal Drilling." 55th U.S. Rock Mechanics/Geomechanics Symposium, 2021.

[3] Barnett, L., Klein, K., Al Dushaishi, M.F., et al. "Field Data Analysis and Modeling of Drillstring Vibrations to Identify Inefficiency in Deep Geothermal Drilling." 55th U.S. Rock Mechanics/Geomechanics Symposium, 2021.

[4] Ejike, C., Obuobi, I. F., Avinu, S., Abid, K., and Teodoriu, C. "Investigation and Analysis of Influential Parameters in Bottomhole Stick–Slip Calculation During Vertical Drilling Operations." Energies, vol. 17, no. 3, 2024, p. 622. https://doi.org/10.3390/en17030622.

[5] Ejike, C., Abid, K., and Teodoriu, C. "Time Domain Modeling of Torsional Stick-Slip in Vertical Wells: A Comprehensive Evaluation with WellScan Simulator." Proceedings of the AADE Fluids Technical Conference and Exhibition, 2024. American Association of Drilling Engineers.

[6] Ejike, C., and T. Shouceng. "Fishbone Technology for Completing Unconventional Reservoirs." Proceedings of the 2021 International Petroleum and Petrochemical Technology Conference (IPPTC 2021), edited by J. Lin, Springer, 2022, https://doi.org/10.1007/978-981-16-9427-1_34.

[7] Ejike, C., and T. Shouceng. "A Method for Reducing Wellbore Instability Using the Managed Pressure Drilling (MPD) System." SPE Nigeria Annual International Conference and Exhibition, 2022, https://doi.org/10.2118/211902-MS.

[8] Obuobi, I., Ejike, C., Abid, K., and Teodoriu, C. "Investigating the Mechanism, Impact and Mitigation of Stick-Slip Vibrations in Drilling Opertaions." Proceedings of the AADE Fluids Technical Conference and Exhibition, 2024. American Association of Drilling Engineers.

[9] Barnett, L., Klein, K., Al Dushaishi, M. F., Nygaard, R., and G. Hareland. "Field Data Analysis and Modeling of Drillstring Vibrations to Identify Inefficiency in Deep Geothermal Drilling." Paper presented at the 55th U.S. Rock Mechanics/Geomechanics Symposium, Virtual, June 2021.

[10] AlRassas, A. M., et al. "Knowledge-Based Machine Learning Approaches to Predict Oil Production Rate in the Oil Reservoir." In: Lin, J. (Ed.), Proceedings of the International Field Exploration and Development Conference 2023. IFEDC 2023. Springer Series in Geomechanics and Geoengineering, Springer, Singapore, 2024, https://doi.org/10.1007/978-981-97-0268-8_24.

[11] Liu, Hong, Irving P. Girsang, and Jaspreet S. Dhupia. "Identification and Control of Stick–Slip Vibrations Using Kalman Estimator in Oil-Well Drill Strings." Journal of Petroleum Science and Engineering, vol. 140, 2016, pp. 119–127. ScienceDirect, https://doi.org/10.1016/j.petrol.2016.01.017.

[12] Riane, R.; Doghmane, M.Z.; Kidouche, M.; Tee, K.F.; Djezzar, S. Stick-Slip Vibration Suppression in Drill String Using Observer-Based LQG Controller. Sensors 2022, 22, 5979. https://doi.org/10.3390/s22165979.

[13] Kamel, J.M., and Yigit, A.S. "Modeling and Analysis of Stick-Slip and Bit Bounce in Oil Well Drillstrings Equipped with Drag Bits." Journal of Sound and Vibration, vol. 333, 2014, pp. 6885–6899, https://doi.org/10.1016/j.jsv.2014.08.001.

[14] Richard, T., Germay, C., and Detournay, E. "A Simplified Model to Explore the Root Cause of Stick-Slip Vibrations in Drilling Systems with Drag Bits." Journal of Sound and Vibration, vol. 305, 2007, pp. 432–456, https://doi.org/10.1016/j.jsv.2007.04.015.

[15] Al Dushaishi, M.F., Nygaard, R., Andersen, M., et al. "Selecting Optimum Drilling Parameters by Incorporating Vibration and Drilling Efficiency Models." SPE/IADC Drilling Conference Proceedings, 2016, https://doi.org/10.2118/178834-MS.

[16] Nandakumar, K., and Wiercigroch, M. "Galerkin Projections for State-Dependent Delay Differential Equations with Applications to Drilling." Applied Mathematical Modeling, vol. 37, 2013, pp. 1705–1722, https://doi.org/10.1016/j.apm.2012.04.038.

[17] Yigit, A.S., and Christoforou, A.P. "Stick-Slip and Bit-Bounce Interaction in Oil-Well Drillstrings." Journal of Energy Resources Technology, vol. 128, 2006, pp. 268–274, https://doi.org/10.1115/1.2358141.

[18] Besselink, B., Van De Wouw, N., and Nijmeijer, H. "A Semi-Analytical Study of Stick-Slip Oscillations in Drilling Systems." Journal of Computational and Nonlinear Dynamics, vol. 6, 2011, https://doi.org/10.1115/1.4002386.

[19] Sharma, A., Al Dushaishi, M., and Nygaard, R. "Fixed Bit Rotary Drilling Failure Criteria Effect on Drilling Vibration." 55th U.S. Rock Mechanics/Geomechanics Symposium, June 2021.

[20] Dunayevsky, V. A., Abbasslan, F., and Judzis, A. "Dynamic Stability of Drillstrings Under Fluctuating Weight on Bit." SPE Drilling & Completion, vol. 8, no. 4, 1993, pp. 84-92.

[21] Dykstra, M. W., Chen, D. C.-K., Warren, T. M., and Zannoni, S. A. "Experimental Evaluation of Drill Bit and Drillstring Dynamics." Proceedings of the SPE Annual Technical Conference and Exhibition, New Orleans, 25–28 Sept. 1994, SPE-28323.

[22] Kriesels, P.C., Keultjes, W.J., Dumont, P., Huneidi, I., Furat, A., Owoeye, O.O., and Hartmann, R.A. "Cost Saving Through an Integrated Approach to Drill String Vibration Control." Proceedings of the SPE/IADC Middle East Drilling Technical Conference, 8–10 Nov. 1999, Abu Dhabi, UAE.

[23] Leine, R.I., van Campen, D.H., and Keultjes, W.J.G. "Stick-Slip Whirl Interaction in Drillstring Dynamics." Journal of Vibration and Acoustics, vol. 124, 2002, pp. 209–220.