CALCULATION OF TORQUE AND DRAG ON THE DRILL STRING IN DIRECTIONAL DRILLING USING A BOND GRAPH APPROACH

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ABSTRACT

Deriving a torque and drag for deviated wellbore are challenging due to complex wellbore profile and the irregular contact between the string and the wellbore. To simplify derivation, most models in the literature have ignored the stiffness of the drill string and have assuming constant contact with the wellbore. However, these "soft-string" models have limited accuracy. On the other hand, most "stiff-string" models rely on computationally demanding Finite Element Analysis (FEA) models or unrealistic assumptions. To mitigate these issues, a 2D stiff string torque/drag bond graph model was developed using Multi-Body Dynamics (MBD) methodology and was implemented in the 20 sim™ software package. This string model is divided into small rigid segments with springs attached between them to emulate flexibility and the contact was modeled using non-linear springs placed between segment endpoints and the wellbore. Furthermore, this model was quantitatively validated using a similar MSC ADAMS™ model.

Keywords: 2D rigid body motion, multibody dynamics, 20 sim™, drilling, torque and drag

1 INTRODUCTION

Directional drilling is a modern drilling technique that involves drilling at non-vertical angles, including horizontal. This technology enables the exploration of multiple oil reservoirs with a single well, thus reducing the cost and environmental impact. Moreover, directional drilling permits the exploration of inaccessible oil reservoirs using conventional drilling techniques, enabling more opportunities and financial benefits. (Fernando 2020)

Although directional drilling was first introduced in the 1920s, it was not widely used in the industry due to its inefficiency and inaccuracy. However, by using modern technologies and equipment, engineers have resolved most of these issues. Furthermore, with increased accuracy and efficiency, directional drilling has gained significant importance in recent years. In 2019, the directional drilling industry was valued at USD 8.8 billion and is anticipated to reach USD 20.3 billion by 2027 (Dataintelo 2020).

One of the main problems in directional wells is the high torque and drag applied to the drill string. High torque and drag will reduce rate-of-penetration, cause severe case wear, and are considered as the main limiting factor for the well's maximum horizontal reach (Aadnoy and Kaarstad 2006). Hence, minimizing torque/drag and accurately predicting friction is vital for the successful completion of the drilling operation. Therefore, many researchers have dedicated their effort to derive accurate friction models. However, most of these friction models are derived using geometrical simplifications and formulas that are specific for a given well trajectory.

To mitigate this issue, a novel approach for calculating torque and drag using contact between the wellbore and drill-string is derived in this research work. In this approach, the contact force was calculated using the wellbore profile and the

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relative location of the drill string segments. To calculate the relative location, an MBD model was used. A detailed description of this methodology will be provided in later sections.

This contact-based friction model enables easy calculation of friction and drag for different well trajectory profiles. Moreover, it can be easily modified to include friction and drag force from other tools in the drill string, such as tool joints and stabilizers. Furthermore, since this friction model is applicable for any trajectory profile, it can be used to determine the optimal well trajectory to minimize the torque and drag on the drill string. Additionally, this research work can be easily adapted to predict the drilling string's failure criteria and fatigue life in directional drilling. companion.

2 BACKGROUND

2.1 Torque and drag issues in directional drilling.

Due to the drill string's lateral movement, drag occurs, and due to its rotation, frictional torque occurs. In some extreme situations, this frictional torque can cause shear failure in the drill string. Consequently, maximum drilling depth in many directional drilling projects is determined considering the maximum frictional torque and drag throughout the profile and the material strength of the drill string. Therefore, it is essential to evaluate these parameters during the planning stage to avoid catastrophic failure or premature termination of the drilling operation (Adewuya and Pham 1998).

Moreover, excessive torque and drag in extended reach wells can lead to high over pulls, severe casing wear, and potential buckling problems (Aston, Hearn and McGhee 1998). Furthermore, this additional torque and drag on the drill string will reduce penetration rate (ROP) and induce torsional vibrations and instabilities in the drill string (Altamimi, Mokrani and Zulfikaf 2015). Therefore, to mitigate these issues, it is crucial to develop an accurate friction model.

2.2 Torque and drag model review.

The torque and drag models developed in the literature can be divided into two main categories, soft string models and stiff string models. In the soft spring model, the stiffness of the drill string is neglected. Therefore, the drill string is assumed to maintain constant contact with the wellbore. Hence, the shape of the drill string is consistent with the curvature of the wellbore. Because of these assumptions, deriving soft string torque and drag models is significantly less complex when compared with stiff string models. However, the accuracy of soft string models is debatable, especially for heavy-weight drill pipes (HWDP) and drill collars.

In stiff string models, as the name implies, the stiffness of the drill string is also taken into consideration when deriving the torque/drag model. Due to drill string stiffness, it does not maintain constant contact between the wellbore surfaces. The complex contact characteristics between the wellbore and the drill string are challenging to derive using an analytical approach. Thus, most stiff string models use an FEA approach, which will be more computationally demanding. However, few research works have managed to derive simple analytical stiff string torque/drag models. But most of these research works still depend on the constant contact assumption.

2.2.1 Examples for soft string models.

The earliest soft string friction model was derived by Johansick, Friesen and Dawson (1984), who defined the frictional force as the product of normal force and friction coefficient. The normal force was calculated using the vector sum of the buoyed weight of the drill string element and the two axial tension forces at the ends of the drill string. Afterwards, Sheppard, Wick and Burgess (1987) improved the Johansick model by considering the mud pressure and changing the model into standard differential equation form. Furthermore, Ho (1988) improved the Johansick model by adding a stiff collar section representing the bottom-hole assembly (BHA) with an improved soft-string model for the remainder of the drill string.

Aadnoy and Anderson (2001) derived an analytical expression for wellbore friction considering various well geometries. Additionally, this paper introduced a new modified catenary wellbore profile. The catenary shape is the natural shape of a drill string (or a hanging chain) and theoretically enables the drill string to hang freely inside the wellbore, reducing torques and drag on the drill string. However, Aadnoy and Kaarstad (2006) presented another paper demonstrating that catenary profiles are not as favorable as previously expected due to the friction in the catenary entrance/exit and suggested using friction reduction measures at these points. Additionally, by identifying many new symmetries in the previously derived friction models, Aadnoy and Djurhuus (2008) were able to derive a new simpler friction model with only two equations; one for torque and one for drag.

2.2.2 Examples of stiff string models.

The earliest examples for a stiff string model were developed by Ho (1988), and it was modeled with the continuous contact assumption. This model considers the effects of bending moment and shear forces when deriving this analytical solution. Moreover, this research paper also showed the importance of including the stiffness when modeling the drill-collar and the HWDP. Furthermore, Ho concluded that the soft string models are sufficiently accurate for very smooth wellbore trajectories with low tortuosity. Similarly, McSpadden and Newman (2002) concluded that soft-string models are working perfectly for most cases unless for Dog Leg Severity (DLS) higher than 30°/100 ft and for stiffer tubular sections such as drill-collars.

Furthermore, Menand, Sellami and Tijani (2006) developed a stiff string model using the FEA approach. The clearance between the wellbore and the drill string was also considered when deriving the model. Moreover, this algorithm calculates the unknown contact points between the drill string and the wellbore and applies a non-linear spring that generates the contact force.

Moreover, Aadnoy, Fazalizadeh and Hareland (2010) developed a stiff string model by combining previously derived models. This model is based on the analytical approach instead of the time-consuming FEA approach. Therefore, to make the model derivation less complex, the wellbore was assumed to have a constant curvature, and the drill string was assumed to maintain constant contact with the wellbore. Moreover, this research paper also provides an excellent review of existing soft/stiff torque and drag models.

2.3 Bond graph approach

The bond graph is a multidisciplinary modeling approach that graphically represents the energy structure of a system using only a few different element types. Moreover, bond graph notation provides a concise description of a complex system and aids the formulation of an explicit/implicit system of differential equations. These differential equations are then utilized to simulate the dynamic behavior of the system (Sarker 2017).

The bond graph method has been used in many previous research works to model the drill string and its characteristics. For example, Rideout *et al*. (2013) have used the bond graph approach to model the drill string's dynamic behavior to study the drill string's vibrational characteristics. They have developed their model by dividing the drill-string into rigid lumped segments and have used lateral, axial, and torsional springs to connect those segments forming a string. This approach incorporates the flexibility of the drill string into the model. Moreover, in this model, the coupling of axial and torsional motion of the drill-string will occur at the bit-rock interface. Furthermore, the frictional torque and drag forces on this model were included in this model based on the equations derived by Aadnoy and Kaarstand (2006).

3 DESCRIPTION OF THE MODEL

The model development process can be divided into few main stages, and in the first stage, model parameters, assumptions, and limitations were identified. Next would be the development of the horizontal and vertical penetration calculation methodology. Afterward, a 2D bond graph model will be developed to model the torque/drag of the drill string using contact forces. Finally, to validate the developed bond graph model, it will be compared against a similar model developed in the MSC Adams™ software package.

3.1 Model parameter calculation

Axial, torsional, bending, and shear spring parameters of drill-string segments can be calculated using the equations given by Rideout *et al*. (2013)

$$k_{axial} = EA/\Delta z \qquad (01)$$

$$k_{torsional} = GJ/\Delta z \qquad (02)$$

$$k_{bend} = EI/\Delta z \qquad (03)$$

For the equations given above, E is the elastic modulus, G is the modulus of rigidity, J is the polar moment of area, A is the cross-sectional area, and I is the area moment.

Due to high contact stiffness and low penetration depth, it would be sufficiently accurate to use Hooke's contact model for this research. Moreover, parameters for the contact stiffness between the wellbore and the drill string can be calculated using experimental results or using datasheets. Furthermore, lubricity from the drilling mud can also be included in the frictional coefficient.

3.2 Calculating contact penetration of the drill string into the wellbore

An intuitive mathematical approach was used to calculate the contact penetration of the drill string with the wellbore. In this approach, the curvature profile of the wellbore centerline was modeled using a mathematical expression. Due to the complexity of the wellbore profile, the derived equation is not a continuous equation but a group of equations that are developed for the build, hold and drop sections of the directional drilling profile. Next, these equations were combined using if conditions inside 20sim™ to form a continuous

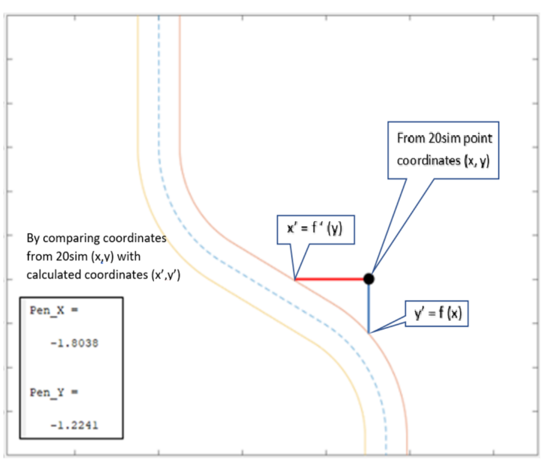

Figure 1: Contact penetration calculation.

wellbore profile. Afterward, by offsetting the wellbore centerline curve by the wellbore radius, the curves for wellbore top and bottom edges were calculated.

The contact force was calculated in both horizontal and vertical directions separately at the top/bottom points of each drill string segment based on endpoint penetration, and the resultant of these forces will be the total contact force applied on that drill string segment. To calculate horizontal penetration, the string segment endpoints in Cartesian coordinates are taken from 20sim for a given simulation time step. Next, using the y coordinates of the drill string segment from the simulation and using the derived equation for the wellbore, the x` coordinates at the top/bottom edges of the wellbore for the given y plane are calculated. Afterward, the penetration in the x-direction is calculated by comparing the x coordinates of the string segment from the simulation with the calculated top/bottom wellbore edge point. A similar approach is taken to calculating the contact penetration in the y-direction. This calculation methodology is shown in Figure 1.

3.3 Development of 2D bond graph model

For developing the 2D bond graph model, the drill string is divided into rigid segments, and springs were placed between them to include the drill string's torsional, axial, and shear stiffness. Furthermore, non-linear springs were attached to each end of the string segments to emulate contact between the string and the wellbore. These springs will have zero force until the endpoints in drill string segments contact the wellbore. In this simulation, the total length of the string was modeled above the wellbore and was slowly lowered. After lowering the drill string and allowing the system to reach stable conditions, contact forces at each string segment point were measured, and torque/drag was calculated using these contact forces by applying Coulomb friction law.

The bond graph sub-model of the drill string segments is shown in Figure 2, and the complete drill string was assembled using a number of these links, as shown in Figure 3. In this model, a modulated flow source was applied to the y-direction of the starting point of link01 to replicate

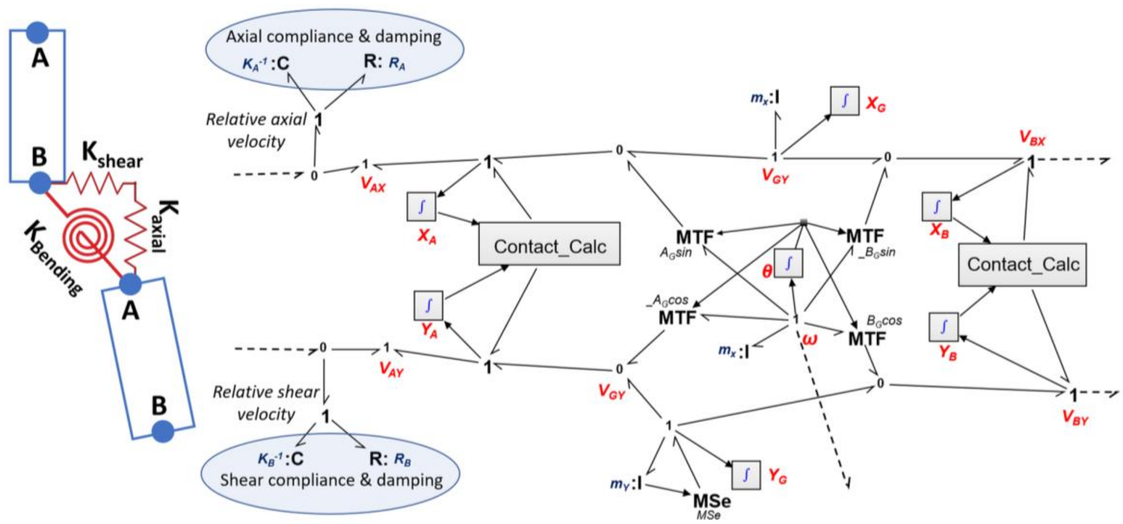

Figure 2: 20sim model of the drill string segment.

the lowering of the drill string into the wellbore. Moreover, the complete 20sim model was developed using reconfigurable parameters, enabling users to modify the drill string and wellbore parameters such as the starting length of the build section, the dogleg severity, and the total length of the wellbore, thus facilitating the easy implementation of this model in various projects.

3.4 Assumptions and limitations

The main limitation of this model is that it is applied on a 2D plane and does not include the wellbore curvature in the z-direction. Another limitation is that the curvature of the two interacting surfaces was neglected when deriving the methodology to calculate the contact force. However, both of these assumptions were taken to simplify the model derivation process and can be easily modified in the future if these assumptions cause any issues.

To simplify contact force calculation, the penetration depth of the drill string into the wellbore was calculated for x and y-direction separately, and using this method will result in higher penetration length than the actual. However, considering that the penetration depth is small, this assumption would not cause significant errors in the calculation. Moreover, if necessary,

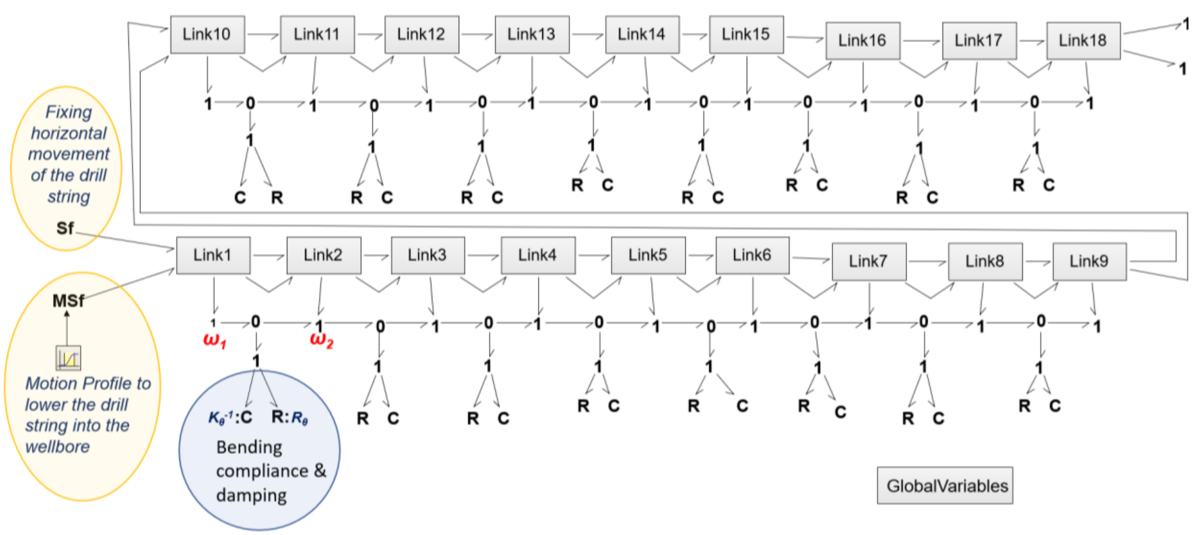

Figure 3: Complete 20sim model

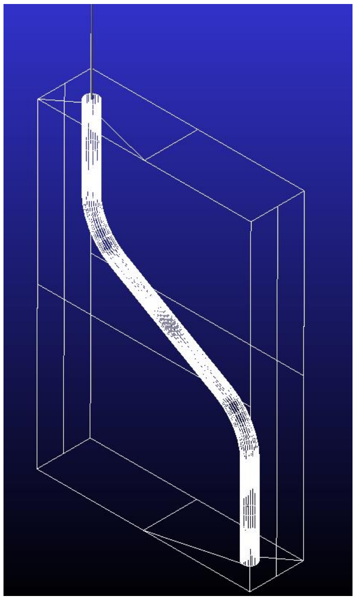

Figure 4: MSC ADAMS™ drill string model.

the actual penetration distance can be calculated using the minimum distance between a point and a curve methodology. This method was not used in this research because it is computationally more demanding and requires obtaining the derivative of the wellbore profile curve.

3.5 Validation of the model

The bond graph model developed in this research work using 20sim™ was validated against an MBD model developed using MSC Adams™. In this model, the drill string is modeled as discrete segments, just like the bond-graph model as shown in Figure 4. However, the contact force was calculated using the built-in function, which is based on the CAD geometries. The comparison between the torque measurements between the Adams™ and 20sim™ model is shown in Figure 5. From these results, it is clear that both models produce similar torque measurements, therefore validating the bond graph contact model derived in this research work.

Moreover, in the 2D bond graph model contact calculation was carried on the end points of the drill string segment and it was assumed that it will not significantly affect the results. This assumption was verified by using the Adams™ as the contact function in that software is based on drill string geometry and analysis contact at all locations of the string.

4 RESULTS AND DISCUSSION

The torque and drag results for a scaled wellbore profile analyzed using the 20 sim™ bond graph software are shown in Figure 6. Moreover, for visualization of the simulation, the line animation tool in 20sim was used, and the output from this tool is also shown in Figure 6. From the output, it can be seen that the drill string does not maintain constant contact with the wellbore, which is the expected behavior and matches with the behavior of a real drill string.

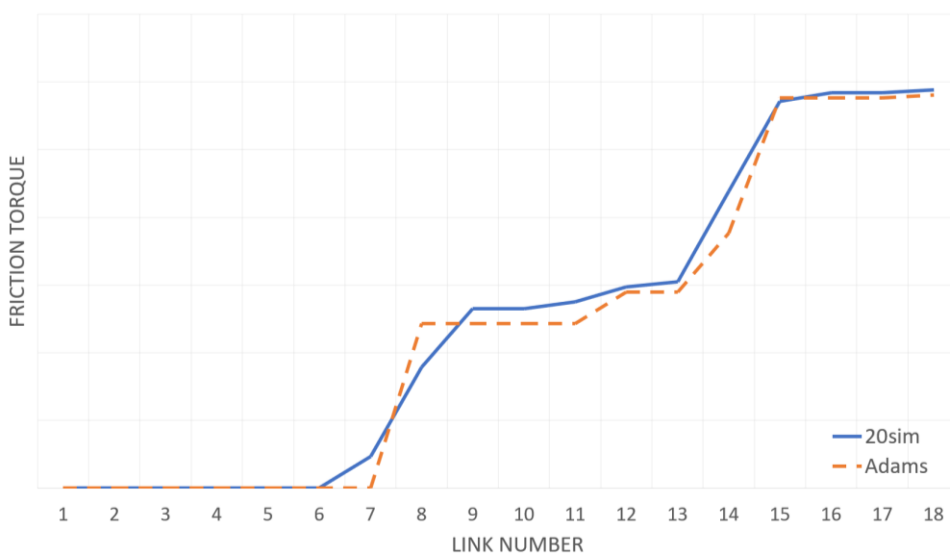

Figure 5: Comparison between the 20sim vs. the MSC Adams results for friction torque

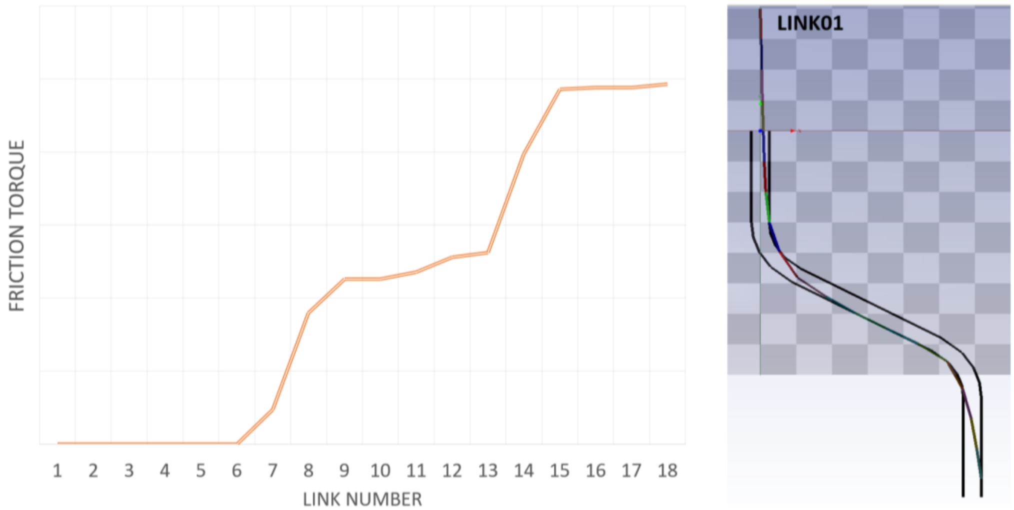

Figure 6: Torque and drag measurements from the 20sim model and output for the animation tool

To further analyze the model correctness and to improve the understanding of the torque/drag behaviors in directional drilling, various scenarios were modeled by changing the parameters of the 20simTM model. The effects of changing the wellbore curvature radius on the frictional torque are shown in Figure 7. The observations from this analysis match the expected behavior. Increasing the curvature will increase the smoothness of the wellbore profile, and due to the smooth profile, the required torque on the drill string will reduce.

Next, the frictional torque variation with changing the wellbore hole diameter was plotted in Figure 8. As expected, increasing the wellbore hole radius has reduced the torque on the drill string. This might be due to having more space inside the wellbore, which will reduce the amount of curvature in the drill string.

After that, the frictional torque variation with changing the drill string stiffness was carried out, and the result from this analysis is plotted in Figure 9. As expected, the increase of the drill string stiffness has increased the frictional torque. Moreover, this analysis also points out the importance of including the string stiffness when calculating the torque/drag in directional drilling.

5 CONCLUSION

The main objective of this research was to develop an accurate and user-friendly torque/drag

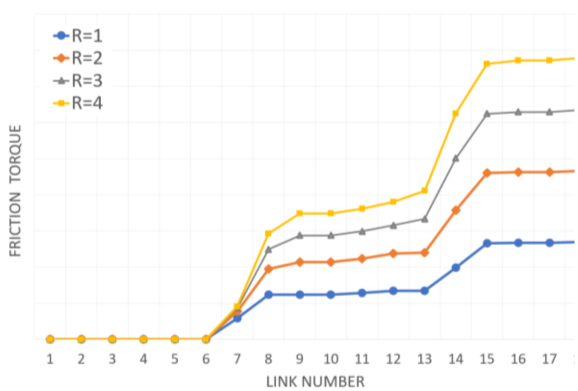

Figure 7: Frictional torque variation with changing wellbore curvature radius.

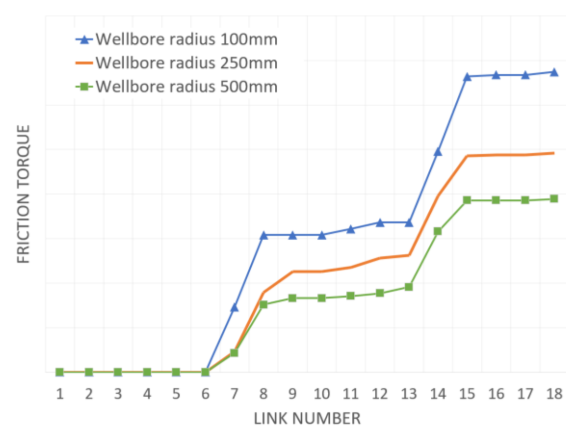

Figure 8: Frictional torque variation with changing wellbore hole radius

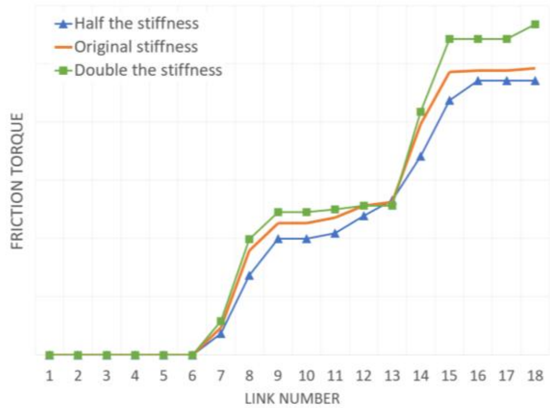

Figure 9: Frictional torque variation with changing drill string stiffness

measurement model for directional drilling using the stiff string approach, and it was achieved successfully. Furthermore, the simulation speed for the scaled drill string model shown in this research was performed almost in real-time. Having a simulation model which produces results quickly is very important for the useability of the model. Moreover, due to the simulation speed, it can be used to check different drilling profiles, and using these simulations, the optimal profile can be selected.

From the results obtained from this research work, it can be concluded that this research work was successful, and the derived model could be easily implemented in future drilling projects. Moreover, due to the model's simplicity, it less computationally demanding when compared with other stiff string models, including the MSC Adams™ model developed in this research. Furthermore, the wellbore profile and the drill string were modeled using parameters, thus enabling easy modification of the derived model to match any wellbore profile and drill string specification.

6 FUTURE WORK

This research can be further improved in the future by validating the model using physical measurements. Moreover, using physical measurements, parameters such as contact stiffness, friction coefficient, and the stiffness of the drill string can be set accurately. Additionally, as previously mentioned, this model can be further improved by changing the model into a 3D model. Thus, the wellbore curvature in the z-direction can also be included in the model.

Furthermore, this model can also be used to study the detailed fatigue analysis using the time-varying stress distribution profile along the drill string's length produced by this model. Additionally, this contact model can be further improved to predict the drill string's vibrational behavior. Using such a model will enable analyzing bit-bound, stick-slip, whirl, and identifying methods to reduce these vibrations. Therefore, the contact model developed in this research will be helpful in many future research works and industrial applications.

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