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360^0 Casing Wear Estimation Using Stiff-String Model Improves Well Integrity

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Abstract

As more complex wells are drilled, issues related to casing, liner and tubing wear increasingly are critical. Regarding casing wear, accurate wear prediction is important for well integrity and optimized well designs. The widely used conventional soft-string model is not applicable for all well paths for casing-wear modeling; it assumes the drillstring continuously follows the exact wellbore curvature and cannot predict different contact locations of drillpipe with the inner casing wall.

Consequently, a new modeling technique has been developed by applying the stiff string model for casing wear analysis. The stiff string model calculates more accurate contact loads by accounting for bending stiffness of the string and helps to estimate the contact position of the drillstring at any given casing depth. These contact points are used to model the development of multiple wear groove locations at any casing depth cross-section by accounting for the varying contact positions as various operations are performed through the casing. Estimates of multiple groove positions at each cross-section reduces the overestimation of casing wear, because the wear is now distributed across different grooves, thus providing a more realistic estimate of casing wear.

This modeling approach was validated by using caliper and ultrasonic logs from various complex wells that are the most susceptible to wear. Detailed operation steps and parameters for each well were modeled to predict the development of multiple wear grooves for each casing section. These models were compared with the 360° cross-sectional distribution of remaining wall thickness from image based ultrasonic logs. The estimated groove depths and positions correlated with the peaks observed from wear logs that show the worst wear locations. The results obtained from this exhaustive analysis are promising to establish a new, more thorough means of validating casing wear predictions.

Introduction

Precise casing wear prediction is important to improve well integrity and longevity, while simultaneously making casing designs more cost effective. Presently, there are no known and commonly accepted guidelines available in the industry. Several studies have been presented in literature over the last couple of decades that proposed various methods to estimate the downhole wear in casings. However, the results of all such efforts have been mixed. Predicted values of casing wear using wear models failed to accurately match the wear logs from the wells when scaled up to the field level.

This paper proposes a new modeling method for casing wear prediction using the stiff string analysis, aiming to reduce the existing uncertainties in downhole wear estimation. In addition to estimating more accurate side forces, the stiff string model also predicts the contact position of the drill string at any given depth in the casing. These contact positions, at any given casing depth cross-section, are used to model the development of multiple wear grooves around the cross-section, as various wellbore operations are conducted through the casing. Further details of this modeling method have been presented in this study.

The proposed model has been validated using measured wear log data from an offshore well in the North Sea. The value of the maximum wear groove depth, along with its respective 360˚ azimuthal location at that casing cross-section measured using the wear logs, were compared with the simulated values for the entire logged casing section. The results correlated well and, thus, help in establishing a more exhaustive field validation of the modeling process. This proposed method will prove to be very useful to improve the accuracy of existing casing wear modeling efforts.

Casing Wear and Well Integrity

Effectively managing well barriers and maintaining well integrity within limits is challenging for aging wells and has a major influence on maximizing the life of wells and reducing operational costs. This is critical not only for the design phase of the well but also for the operational phase. Well Integrity can be broadly considered under the following category:

- Inside the wellbore
- Outside the wellbore
- Beyond the wellbore

Casing wear problems are very critical for all aspects of the above three scenarios as their influence extends beyond the casing wall volume loss. It may affect the wellhead growth, annular pressure build-up and annular volume expansion. The coupling of the models and more accurate estimation of the casing wear volume are important. Absence of casing wear calculation will lead to overestimation of the well integrity and wrong casing wear calculation will lead to underestimation of the well integrity (Fig 1).

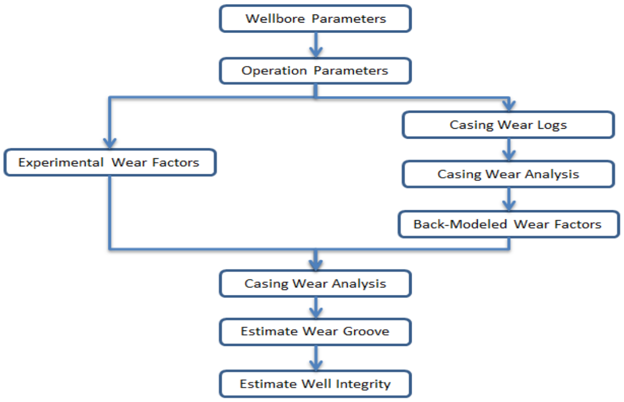


Fig. 1: Casing Wear Estimation.

Casing Wear Model

The fundamental casing wear model used for this analysis is based on the work performed by Hall et al. (1994) from Maurer Engineering Inc. as part of the joint-industry project DEA-42. The model proposed by them is based on the phenomenon that when a rotating tool joint impinges against the inner wall of the casing, a crescent shaped groove is worn in to the inner wall. The underlying assumption of this model was that "the volume of steel removed from each unit length of casing at a point on the inside surface of the casing is proportional to frictional work done at that point by the tool joint rotating in contact with the casing." More details about this modeling method and its underlying parameters, particularly the wear factors, have been presented in the study by Kumar et al. (2015).

This modeling approach has been slightly modified while being applied to address the different kind of operations that are performed to successfully drill a well. Five major operations are considered in this analysis – drilling, backreaming, rotating off-bottom, sliding, and reciprocation. This study focuses on wear caused only by these above operations which can be performed in different sequence to get to the target depth. Each of the operations is further segmented into smaller operation steps of 30 ft each. Other possible reasons for downhole wear such as erosion while fracking, corrosion, or any other mechanical wear during production are not considered in this analysis.

For the drilling and backreaming operations, Eq. 1 below has been applied for analysis. The drilling or backreaming operation starts from a given measured depth, and the drill bit progresses further down (drilling) or up (backreaming) the hole to reach the target end depth for that operation. As a result, the tool joint contact with the inner casing wall varies, as the drill string moves down or up the hole. The last factor in Eq. 1, the ratio of tool joint length over drill pipe length, is applied to account for this contact due to tool joints only. The average side force supported by the tool joints is calculated using Eq. 2, assuming that the entire load is taken by the tool joints only and there is no pipe body contact.

$$WV = W_f \times SF_{tj} \times \pi \times D_{tj} \times RPM \times 60 \times t \times \frac{L_{tj}}{L_p} \quad (1)$$

$$SF_{tj} = SF_{ft} \times \frac{L_p}{L_{tj}} \quad (2)$$

The wear volume for the sliding operation that has no rotations is estimated using Eq. 3. The total sliding distance, d_{sld}, under this scenario is estimated using the starting depth and the end depth of the sliding operation. The wear analysis for sliding is segmented into multiple operation steps, just as in drilling or backreaming. In case, the drill string is rotated at very low rotary speeds while sliding, Eq. 1 is used to estimate wear volume, and this operation becomes similar to drilling for wear volume calculation purposes.

$$WV = W_f \times SF_{tj} \times d_{sld} \times 12 \times \frac{L_{tj}}{L_p} \quad (3)$$

Torque and Drag Model – Soft String vs. Stiff String

The above presented equations for wear modeling clearly suggest that the key to successfully predict the downhole casing wear lies in being able to accurately estimate the normal contact load or side forces acting between the tool joints and the inner casing wall. Higher the value of side forces, higher the expected wear and any inaccuracy in side force calculation will influence the final wear prediction.

The soft string torque and drag model which is often considered as the industry standard has been conventionally used for all wear modeling purposes. This soft string model is considered to represent the real drillstring behavior by neglecting the bending stiffness of the string components so that the entire length of the string behaves as a cable or chain. This model also assumes that the drill string trajectory is the same as the wellbore trajectory to solve the wellbore contact problem, and the contact is further assumed to be continuous along the wellbore.

Even though these assumptions work well for conventional torque and drag analysis, they fail to fulfill the underlying requirements for accurately modeling casing wear. The wear groove predicted using the soft string model is assumed to be concentrated only at one particular location on the low side for any casing cross-section, which does not corroborate the field observations of worn out casings. Additionally, assuming that all the wear is concentrated at only one location along the casing has resulted in over predicting the wear when compared with field wear logs. Furthermore, applying the soft string model for wear analysis in today's complex, deeper and tapered deepwater well configurations could raise potential concerns on the reliability of the well. Hence, to overcome these existing challenges, a more comprehensive stiff string model has been applied for wear analysis in this study.

Mitchell et al. (2009) have presented a detailed background on the drawbacks of the soft string model, and have developed a more comprehensive stiff string model that accounts for bending stiffness of the components, as well as accurately estimates drill string contact points in the wellbore rather than assuming continuous contact. This model is considered more appropriate for advanced wear analysis. The stiff string model estimates more accurate side forces particularly for high dogleg wells as the soft string model has limitations in such scenarios. In addition, it also estimates the contact location of the tool joints with inner casing wall which is used to predict the formation of multiple wear grooves at any casing cross-section that has been commonly observed in the field. Estimating multiple wear groove locations using stiff string is also expected to reduce the over prediction of wear, which has been one of the major drawbacks of the soft string model.

Modeling Multiple Wear Grooves Using Stiff String

As mentioned above, the side force estimated using the stiff string model is considered to be more accurate than the soft string model. This calculated value of side force per ft of drill string is directly applied in Eq. 2 to predict the side force acting on the inner casing wall due to tool joint contact. In addition, the contact location between the drill string and the casing is also estimated for any casing cross-section which is used to model the development of multiple wear grooves.

In this proposed method, the high position and the right position estimates for the drill string location at any cross-section obtained from the stiff string model are used to predict the contact points of the drillstring with the inner casing wall and wear resulting from this contact has been modeled. As any operation conducted through the casing progresses, the contact points of the drillstring vary, and hence wear grooves at different locations of a 360˚ casing cross-section are formed for any given depth. The estimation of multiple wear grooves for any given operation becomes a very complex process due to the sheer number of variables and parameters involved in the modeling technique.

Modeling of multiple wear groves (Fig.2) is highlighted below:

- 10ft Casing Sections Simulated as a 3-D Mesh
- Casing Cross-sections Comprised of 72 Slices
- Wear Volume Allocated Based on Contact Points
- Wear Grooves Modeled Using Crescent Shaped Groove Geometry
- Groove Distribution Resulting From Prior Operations Combined

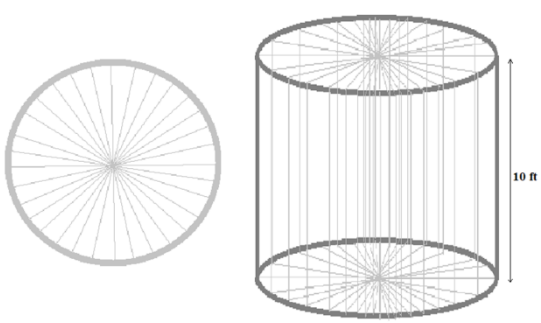


Fig. 2: Slice distribution for each casing section.

Fig. 3 explains the individual steps to compute wear grooves based on the wear volume distribution for each casing section of 10 ft.

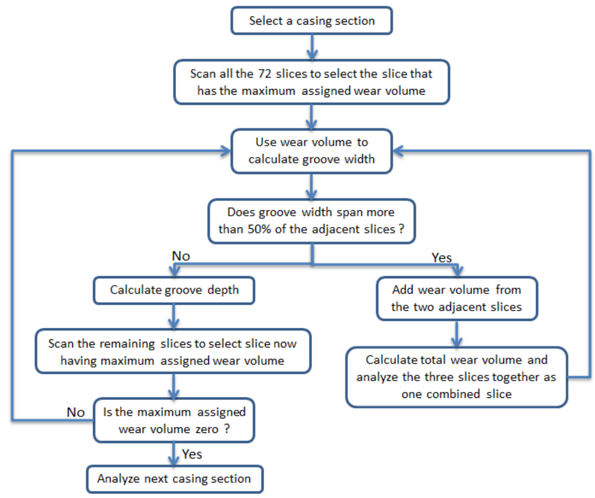


Fig. 3: Method to calculate multiple wear groove distribution based on wear volume slices.

Field Case Study

This developed modeling method has been applied to predict the downhole wear having multiple wear grooves for various complex wells. The results obtained were compared with ultrasonic or caliper wear logs measured from those wells for both the values of wear groove depths and the respective wear groove locations. One such study for an offshore deviated well in the North Sea has been presented here and the well profile has been shown below in Fig. 4. Wear modeling and estimation is performed for the detailed data set from this well, and the results are compared with measured values from an ultrasonic wear log.

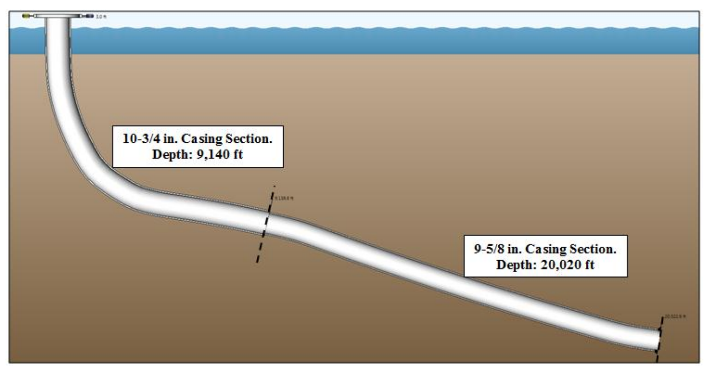


Fig. 4: Schematic well profile used for the offshore well used for field validation.

The results of the modeling simulation were compared with ultrasonic wear log run in the well. Only the 9-5/8 in. casing section was logged between the depths of 9,445 ft and 16,540 ft. The values of minimum remaining wall thickness from the ultrasonic log have been compared with the minimum remaining wall thickness estimated from the modeling approach outlined above. This value of minimum remaining wall thickness corresponds to the wear groove having maximum groove depth, or the worst groove out of the multiple grooves caused at any given cross-section for each 10 ft casing section.

Fig. 5 below shows the estimated casing wear values calculated using the above described modeling approach using the stiff string method. Here, the red regions show the worn out sections of the casing wall, while the regions in green show the wall thickness that is still available to be worn out before reaching the wear limit value. The grey region marks the wall thickness outside the wear limit considered for analysis.

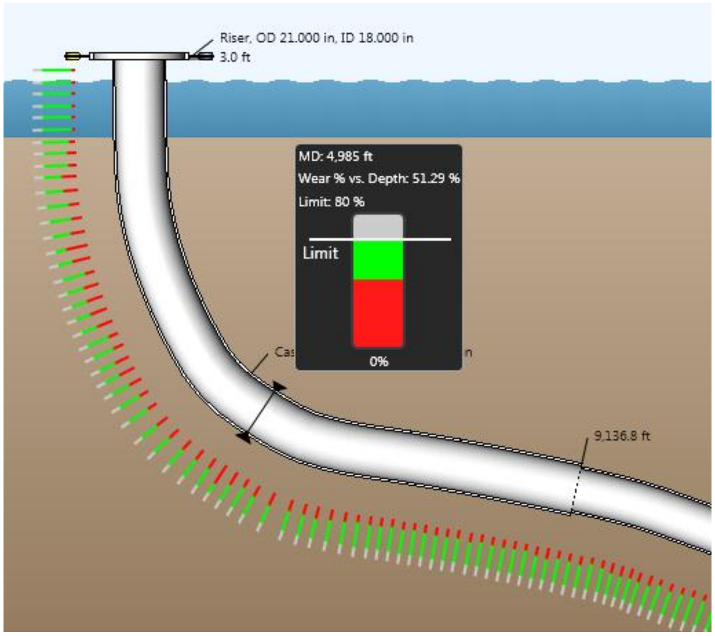


Fig. 5: Casing wear simulated using the stiff string model.

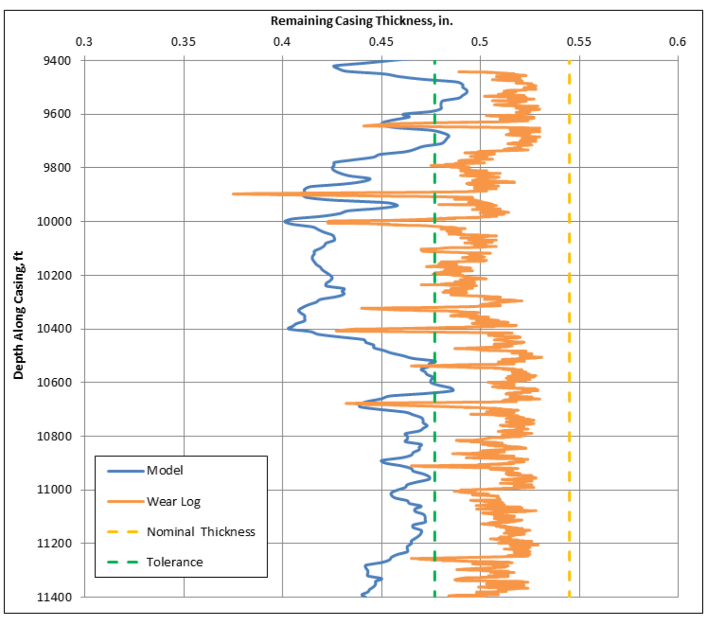


Fig. 6: Remaining casing wall thickness comparison with ultrasonic log for the high wear zone.

For the logged casing section, the measured value of remaining wall thickness using ultrasonic log showed that certain high wear zones existed between the depths of 9,445 ft and 11,400 ft. However, apart from these high wear zones, most of the logged casing section showed that the measured remaining wall thickness lied between the values of nominal wall thickness and the manufacturing tolerance. The downhole wear predicted using the proposed modeling method correlates well with the peaks from the wear log lying in the high wear zone of about 2,000 ft below the top of the logged depth of 9,445 ft. Below this high wear zone, where most of the measured values using the ultrasonic log fall within the tolerance limit, the model tends to over predict the wear. Further investigation of this wear log comparison with the model was divided into two parts – the high wear zone between the depths of 9,445 ft and 11,400 ft, and the low wear zone between 11,400 ft and 16,540 ft, which was the bottom of the logged section.

The wear log comparison of the high wear zone has been more closely highlighted in Fig. 6. Here, the peaks of the ultrasonic wear log lying outside the manufacturing tolerance limit correspond well with the wear distribution for this zone predicted using the model. Estimated wear percent for the worst groove at any casing cross-section falling in the high wear zone varied from a minimum of 10% wear to a maximum of 26% wear. This high wear resulted in reducing the API burst rating of 10,900 psi for the P-110 casing to a minimum value of 8,027 psi only. The API collapse rating for the worn out casing also reduced significantly by 55%, from 7950 psi to a minimum value of 3624 psi. The standard API equations were used to estimate this reduction in the burst and collapse ratings.

The slight variations in wear between the measured log values and the estimated values using the model, is attributed to some of the underlying uncertainties in the input parameters that we used for modeling. As suggested by Kumar *et al.* (2015), total wear predictions are heavily influenced by parameters like wellpath, survey frequency, multiple wear factor distribution along the casing or the drill string, operation parameters like weight-on-bit or rpm, and the downhole wellbore conditions. Variation or inaccuracies in any of these input parameters would in turn influence the final predicted wear. Hence, minor differences in peaks between the wear log and the model may have resulted from variations in any of these above input parameters. For this analysis, a single wear factor value of 3E-10/psi was selected based on the type of casing, drillstring and mud properties, and a more comprehensive wear factor distribution applied for modeling may result in further reducing these observed differences. However, based on the available information from well operations, this chosen value of 3E-10/psi for the wear factor was considered acceptable for wear modeling.

The wear log in the low wear zone between the depths of 11,400 ft and 16,540 ft was examined again to investigate the cause of over prediction of wear using the model. It was concluded that the ultrasonic logging tool used for measuring the value of remaining wall thickness had a limitation on identifying the wall thickness for low wear zones because of the amplitude used while performing measurements. Hence, the tool was correctly able to identify the remaining wall thickness in zones that experienced high wear, and the remaining wall thickness values that were logged below the manufacturing tolerance limit, were regarded as redundant for comparison with the model.

The other important parameter that has been used for validation and comparison between the wear log and the model is the azimuthal location of the worst wear groove at any casing cross-section in the logged zone. Even though the ultrasonic log had limitations on measuring the actual value of remaining wall thickness in the low wear zones, it still was able to capture the azimuthal location of the wear groove for any cross-section. Hence, this information was deemed as very useful for further validation of the proposed multiple wear groove prediction model. Such comparisons between the measured azimuthal location of wear grooves and modeled location of wear grooves have not been performed before for casing wear analysis in the industry, and will help to further understand the accuracy of the underlying modeling method.

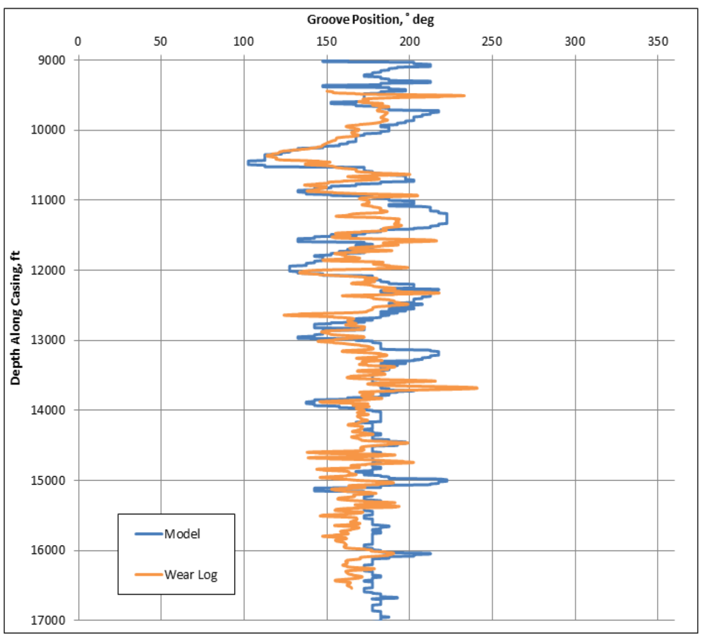
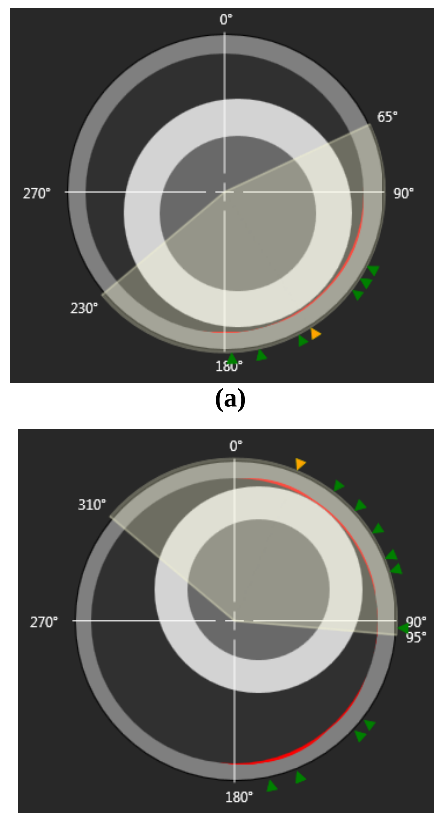


Fig. 7: Wear groove position comparison with ultrasonic log.

Fig. 7 shows the wear groove position comparison between the modeled wear grooves and the ultrasonic wear log. Out of the multiple wear grooves modeled using the proposed method, the azimuthal location of the worst groove having the maximum groove depth has been compared with the log. The high side of the wellbore is considered to be 0˚ in the used convention, and the casing cross-section is traversed in a clockwise direction to model multiple grooves. The logged location of the wear grooves using the ultrasonic log again correlate very well with the location of the worst groove as estimated by the model. It should be noted that the entire logged depth lied in the deviated section of the wellbore, hence, maximum wear was caused on the low side of the casing. Both, the measured and the predicted values in Fig. 7 further confirm this observation as most of groove locations lied on either side of 180˚ that represented the low side.

This type of analysis performed using the model helps to reduce the existing misconceptions in the industry about casing wear predictions, and opens the door for carrying out a more exhaustive wear analysis by effectively using all the data measured by the logging company. This analysis should be used as the new benchmark for wear modeling and estimation.

Fig. 8 shows the multiple wear grooves estimated at two different depths of the casing section. Fig. 8 (a) has been shown here at the depth of 12,960 ft that lies in the deviated section of the well, and conventionally one single wear groove should have been expected in the low side. However, the azimuthal contact locations predicted using the stiff string model show that the wear was distributed between multiple wear grooves lying between 90˚ and 180˚ of the casing cross-section based on the clockwise convention specified above. This location of the maximum wear groove has been marked here with an orange pointer.



(a)

(b)

Fig. 8: Casing cross-section looking downhole showing multiple wear grooves prediction at the depth of 12,960 ft. and 4,510 ft respectively.

The location of the maximum wear groove predicted using the model at the depth of 12,960 ft, matched very well with the azimuthal location of the maximum wear groove measured using the ultrasonic log as shown in Fig. 7. Wear groove distribution at this particular depth of 12,960 ft has been highlighted to further lay stress on the importance of modeling multiple wear grooves. Even though there were depths that experienced higher wear, there was only one large groove at those locations lying on the low side.

Fig. 8 (b) shows the multiple wear grooves distribution for another depth, 4,510 ft that was not logged using the ultrasonic logging tool. The model predicted the development of various different wear grooves mostly around the right side of the casing between 0˚ and 180˚ based on the different operations that were performed in the wellbore. The green pointers mark the positions of all the grooves on the casing cross-section, while the orange pointer again shows the location of the worst groove. This type of modeling to predict multiple wear grooves has only been possible due to the application of the stiff string model that can model the actual contact location between the drill string and inner casing wall.

The conventionally used soft string model that assumes all the wear to be concentrated only on the low side of the casing would have resulted in over prediction of wear by 10% to 15% in certain wear zones along the casing. The results of the soft string model will be relatively closer to those of the stiff string for cases where most of the wear is concentrated in just one particular location of the casing cross-section. The lateral section of a horizontal well will be once such example, as most of the wear will be on the low side. However, as we analyze build sections of these complex wells, or wellbore regions that experience drill pipe and casing contact due to buckling, the soft string model will over predict wear by assuming that all contact was at the same location. Application of stiff string models for wear analysis would be prove to be more accurate and reliable for such casing sections under these operating scenarios.

Conclusions

This study proposes a comprehensive solution to a challenging industry problem and would help improve casing designs in current and future oil and gas wells. The primary conclusions from this study are:

- Casing wear modeling approach using the advance stiff string torque and model has been proposed.
- Stiff string model is used to estimate the development of multiple wear grooves for any casing cross-section.
- Field validation was performed using an offshore well from the North Sea.
- The peaks of the minimum remaining wall thickness measured using the ultrasonic log correlated well with the remaining wall thickness predicted using the model.
- The 360˚ azimuthal location of the wear grooves at any casing cross-section measured using the log, also correlated very well with location of the worst groove as predicted by the model
- This proposed method is expected to reduce the over prediction of wear that was commonly observed when using the conventional soft string model, because the wear is now distributed amongst multiple wear grooves to more accurately simulate the actual downhole conditions.

Acknowledgement

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