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REAL-TIME DOWNHOLE WEIGHT ON BIT (DWOB) AUTOMATION IN DIRECTIONAL DRILLING

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ABSTRACT

This paper introduces the functionality of a new type of Autodriller software system, which can acquire downhole weight on bit (DWOB) based on surface rig measurement. Field tests are performed, including DWOB measured by downhole measuring tools and the hookload below the top drive using a TTS (Torque and Tension Sub). Three sets of drilling data from three horizontal wells in Western Canada were utilized to verify the models of this new Autodriller system. DWOB comparisons between the model and the measuring tools were carried out. The comparisons indicate a good agreement between the downhole measured DWOB and the new Autodriller predicted values. The difference between the new Autodriller prediction and downhole measured DWOB can be quantified using rooted mean square error (RMSE) or relative error (RE). This paper also analyzes the differences in some sections, and some measures are suggested to potentially reduce these differences. The new Autodriller is a closed loop control system which can automatically in real-time adjust surface weight on bit (SWOB) so that the DWOB is accurate, which will directly improve the performance of drill bits, and decrease the cost of drilling, especially in directional well drilling applications.

INTRODUCTION

Oil and gas reservoirs have become increasingly difficult to explore and produce, therefore operators are seeking methods to access these reservoirs and to produce them in the most cost-effective way. One of the methods is to use automatic drilling tools such as an Autodriller. The Autodriller system is usually an automatic self-adjusting weight on bit tool based on SWOB or motor differential pressure. It has been used since the early 1970s. The development of the modern Autodriller has been supported with the rise of more sophisticated mechanical braking and electronic control systems [1]. Designed to reduce

costs by saving drilling hours and extending the life of drill bits, the Pason's AutoDriller maintains a specified weight on bit (WOB) to maximize the rate of penetration (ROP) while drilling. Like a regular Autodriller, the principle of this Autodriller is to actuate the drilling rig's drawworks brake handle using continuous feedback from hookload, drilling fluid pressure, drawworks drum rotation, and a target ring depth sensor [2]. Another Autodriller automatically maintains deadline tension, enabling a constant penetration rate for fast and efficient drilling. This durable driller reduces drilling costs, increases bit life, and helps ensure an accurate drilling path [3]. The NOV's electronic drilling system delivers performance, including improved bit wear, improved safety, enhanced rig efficiency, and a higher quality wellbore. The design of the system provides the precise control and performance needed in conventional and unconventional drilling operations—the high count stepper motor and improved control algorithms improve the drilling control and results. This system offers more information at a glance through an easier setup, and operation via the driller's screen, allowing to maximize the potential of the Autodriller [4]. The Rigserv developed an advanced and comprehensive integrated automatic drilling and travelling block safety system. It utilizes state-of-the-art PLC and touchscreen control technology with comprehensive software designed to optimize drilling control and drilling safety, complete with reliable sensors and control interfaces. Normal steady drilling functions carried out by the driller can be performed by the system with far more precision, consistency, and safety, due to the fact that all related drilling variables are integrated and interacting simultaneously [5]. However, these Autodrillers, which are called the regular Autodrillers, are still conservative where an excessive potential safety margin is applied to prevent damage to the drill bits and as a result in some cases the optimal performance of the drill bits cannot be achieved. New mathematic models and software in real-time

drilling have played a very important role in the development of a new Autodriller system. This new type of Autodriller is used in real-time to get accurate downhole weight on bit, and can shorten or remove the potential difference margin and realize a better performance optimization of drill bits [6, 7].

AUTODRILLER MODEL

The authors of this paper have been seeking better ways of improving drilling operations and decreasing costs by the use of advanced real-time modeling and simulation technologies. It is well known that the performance of a drill bit directly affects the overall drilling performance. The bit performance is often evaluated by the rate of penetration which is dependent on the weight on bit [8]. Therefore, obtaining actual DWOB is crucial in achieving good performance of a drill bit. The torque and drag (T&D) model referred to herein is based on other researchers' models [9, 10] and is introduced as follows.

An element of the drillstring is utilized as an object to analyze the forces applied on it (shown in figure 1). The wellbore is composed of straight vertical, inclined straight and curved sections.

For straight sections the axial force at the top end of the element can be expressed as the following.

$$F_i = F_{i+1} + \beta_i w_i \Delta L_i \cos \alpha_i - \mu \beta_i w_i \Delta L_i \sin \alpha_i \quad (1)$$

For curved sections

If F_{i+1} is positive

$$F_i = F_{i+1} \times e^{-\mu|\theta|} + \beta_i w_i \Delta L_i \times \left[\frac{\sin \alpha_i - \sin \alpha_{i+1}}{\alpha_i - \alpha_{i+1}} \right] + \mu \beta_i w_i \Delta L_i \times \left[\frac{\cos \alpha_i - \cos \alpha_{i+1}}{\alpha_i - \alpha_{i+1}} \right] \quad (2)$$

Where

$$\theta_i = \arccos(\sin \alpha_i \sin \alpha_{i+1} \cos(\phi_i - \phi_{i+1}) + \cos \alpha_i \cos \alpha_{i+1}) \quad (3)$$

If F_{i+1} is negative

$$F_i = F_{i+1} + \beta_i w_i \Delta L_i \cos \alpha_i - \mu F_n \quad (4)$$

Where

$$F_n = [(F_{i+1}(\phi_i - \phi_{i+1}) \sin(\frac{\alpha_i + \alpha_{i+1}}{2}))^2 + (F_{i+1}(\alpha_i - \alpha_{i+1}) + \beta_i w_i \Delta L_i \sin(\frac{\alpha_i + \alpha_{i+1}}{2}))^2]^{1/2} \quad (5)$$

Based on this model, the new Autodriller software system has been developed. Figure 2 shows the flow chart of the new Autodriller. The green box is the flow chart of a typical regular Autodriller. The regular Autodriller works by automatically controlling the drum rotation or the brake handle of a drawworks to make the WOB from the deadline sensor equal to the target WOB from a computer. The red box represents the current T&D model/software. This T&D model/software can predict DWOB using the surface measurement. Integrating the model/software with a regular Autodriller the new Autodriller is created, and it can apply more accurate weight on bit for directional/horizontal applications.

MAIN FUNCTIONALITY

- Post analysis can be done with drilling data of completed wells.

- Real-time calculation of friction factor and downhole weight on bit.
- SWOB can be obtained real-timely based on target DWOB.
- Real-time monitoring compression/tension to prevent drillstring from buckling or strength failure.
- Real-time monitoring downhole torque on bit (DTOB) and DWOB to prevent bounce/whirling of the bits.
- Real-time optimization of ROP based on drilled data.

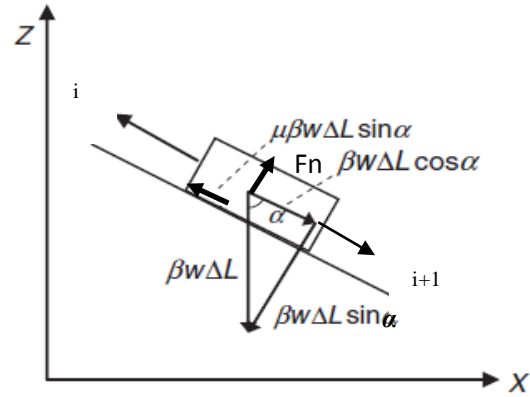


FIGURE 1. Force analysis of an element

Using collected drilling data, post analysis can be carried out with the T&D model/software application. Figure 3 shows the results of a post analysis. The results from the post analysis can be used as a reference for drilling off-set wells with similar rigs and drilling conditions such as similar wellbore geometry and drillstring configuration.

The T&D model/software can by design be used for drilling in real-time after calibration. The model was calibrated initially using the drilling data from a section in a horizontal well by manually adjusting the sheave efficiency and standpipe pressure (SPP) effect coefficient to match the measured DWOB with those calculated by the model. The rough SPP effect coefficient can be obtained by analyzing the relationship between hookload and SPP. Then the adjusted sheave efficiency and SPP effect coefficient are used to do the prediction for the rest sections of that well [7]. The results for three wells presented in this paper are obtained by using the same sheave efficiency and SPP effect coefficient. In other words, it is not to use different coefficients to do the matches for three wells. Thus the T&D model/software system can real-timely predict and display downhole WOB, downhole torque on bit, and other key drilling parameters (shown in figure 4). For example it can monitor the compressive force in the string, a warning will be sent immediately if it approaches some value which causes the buckling.

INPUT AND OUTPUT

The modeling requires general rig data and operational parameters.

Input

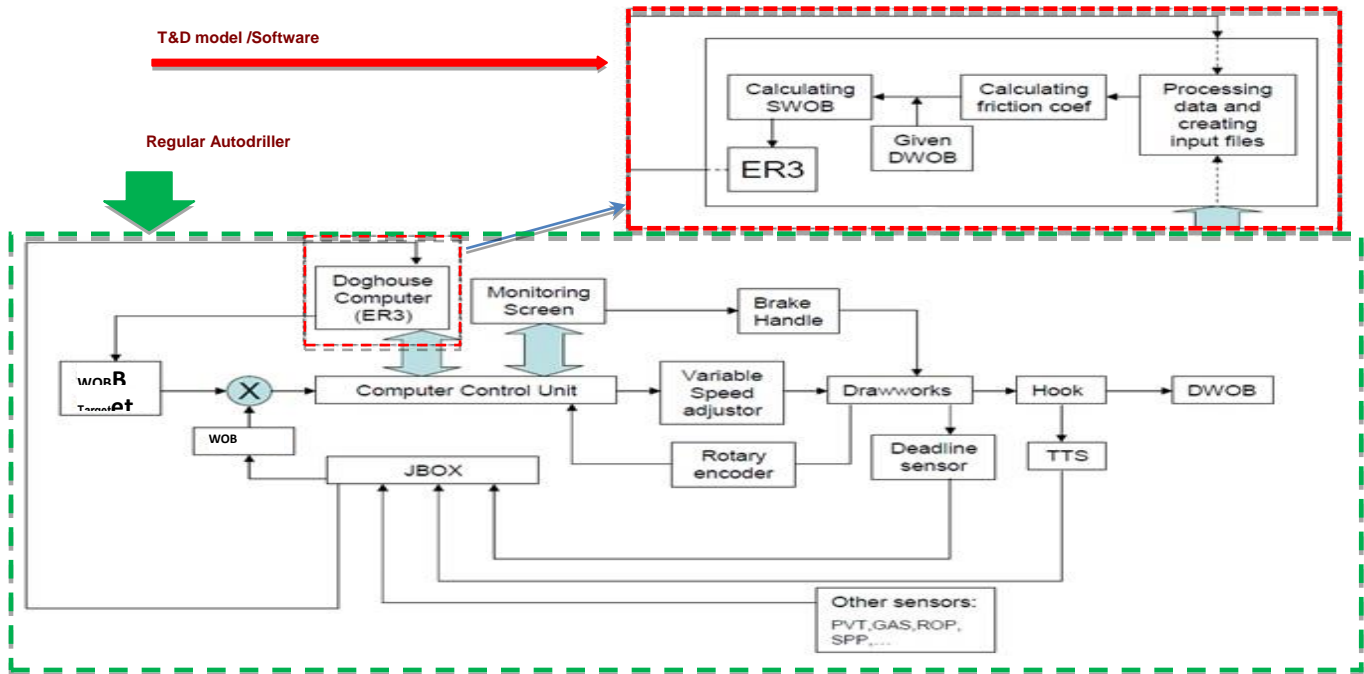


FIGURE 2. Flow chart of the new Autodriller

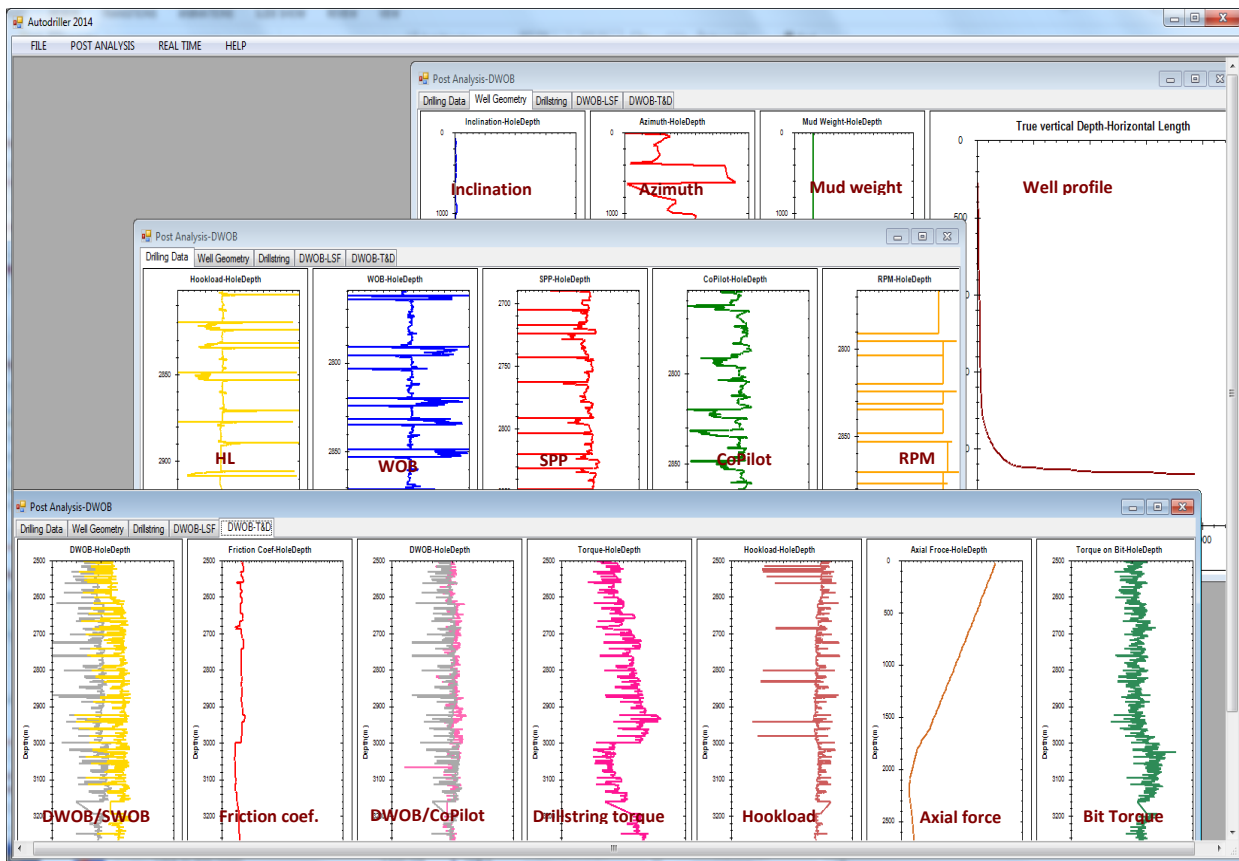


FIGURE 3. Post analysis

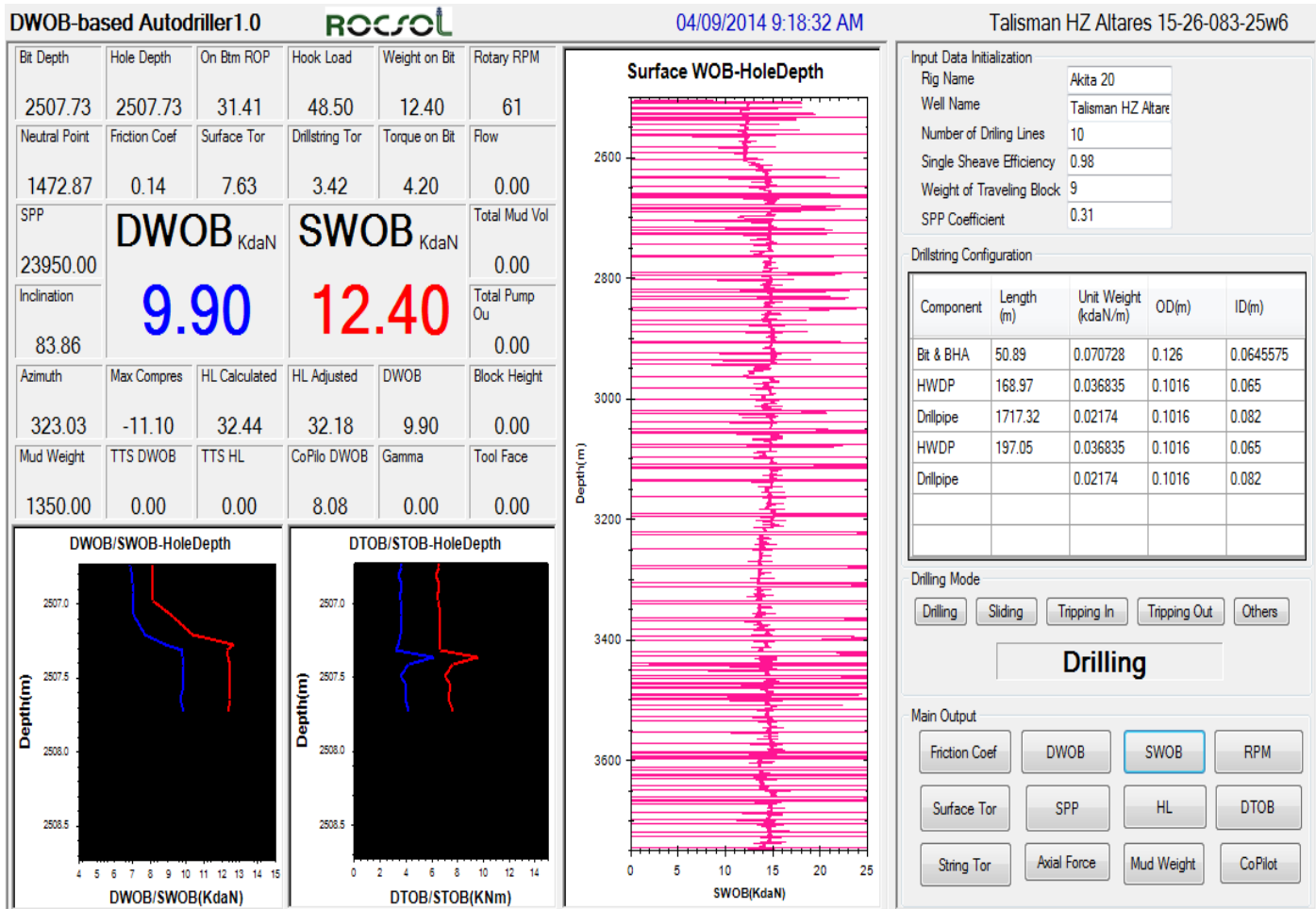


FIGURE 4. Real-time monitoring of drilling operation

- Off-bottom data after every connection: Bit depth, hole depth, WOB, RPM, hookload, SPP, differential pressure, and etc.
- Survey data : Measured depth, azimuth, inclination and TVD
- Drill string configuration : Drill string components such as, section lengths, inner and outer diameters, unit weights
- Additional parameters: Single sheave efficiency, weight of traveling block, number of lines between blocks etc.

Output

- Friction coefficient at each connection
- Effective surface weight on bit
- Downhole torque on bit, axial compression/tension on drillstring, and etc.

DWOB MEASUREMENT IN THE FIELD

In order to verify the model of the new Autodriller, downhole measurement data, especially downhole weight on bit and downhole torque on bit, is required. It is noted that this kind of downhole measurement is costly. That is why the T&D model/software system was developed in this paper. For measurement of DWOB and DTOB, strain gauges are utilized to measure strain at the locations of the drill string just above the drill bit. Two downhole measurement tools for measuring DWOB and DTOB were used, and one surface measurement sub for measuring hookload was used below the top drive.

CoPilot Tool

The CoPilot downhole tool represents the industry's most advanced and versatile downhole drilling dynamics data acquisition and processing system. It can measure more than 15 parameters down hole at the same time.

EMS Tool

Through application of extensive measurements knowledge and experience, the EMS delivers custom solutions to drilling

challenges such as stick-slip, whirl, and borehole quality. This allows the tool to optimize drilling performance and reduce well delivery costs.

In addition to the above DWOB measurement tools, a new type of sub called tension & torque sub (TTS) can be used to measure the hookload below the top drive. This hookload can be used to calculate more accurate DWOB in that it removes the uncertainty of sheave efficiency. Theoretically, it will produce more accurate results.

Three sets of drilling data from three horizontal wells in Western Canada are extracted from a drilling data service company and used to verify the model of this new Autodriller system. The result analysis is seen in the following sections.

COMPARISON BETWEEN THE MODEL AND FIELD DATA

Figure 5 shows the DWOB comparison between the prediction and the measurement for three wells. On Well#1 and #2 the downhole data is measured by the CoPilot and on Well#3 the downhole data is measured by EMS. The comparison between the calculated and measured values is both in trend and values very good. However, there exist some differences between the model and the measured in some sections.

DISCREPANCY

As mentioned in the previous section there exist difference between the measured and the calculated DWOB. ϵ_{RMSE} and ϵ_{avg} as shown in Eqs (6) and (7) can be used to reflect the

discrepancy between the predicted DWOB and measured one. ϵ_{RMSE} is sensitive to big differences. ϵ_{avg} reflects the whole proximity.

$$\epsilon_{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (\epsilon_i)^2} \quad (6)$$

$$\epsilon_{avg} = \frac{1}{N} \sum_{i=1}^N |\epsilon_i| \quad (7)$$

Where

$$\epsilon_i = \frac{DWOB_p - DWOB_m}{DWOB_m} \quad (8)$$

Table 1: ϵ_{RMSE} and ϵ_{avg} for the three wells

	Well 1	Well 2	Well 3	Average
ϵ_{RMSE}	0.174	0.250	0.207	0.21
ϵ_{avg}	0.103	0.171	0.155	0.143

Figure 6 shows the friction coefficient for the three wells. The process of the friction coefficient calculation is like this: given a coefficient, then the friction force or drag between the drillstring and wellbore can be calculated; and then the hookload can be obtained with the model; finally the hookload calculated is compared to the field hookload; repeat the above steps till the two hookloads are equal within a tolerance.

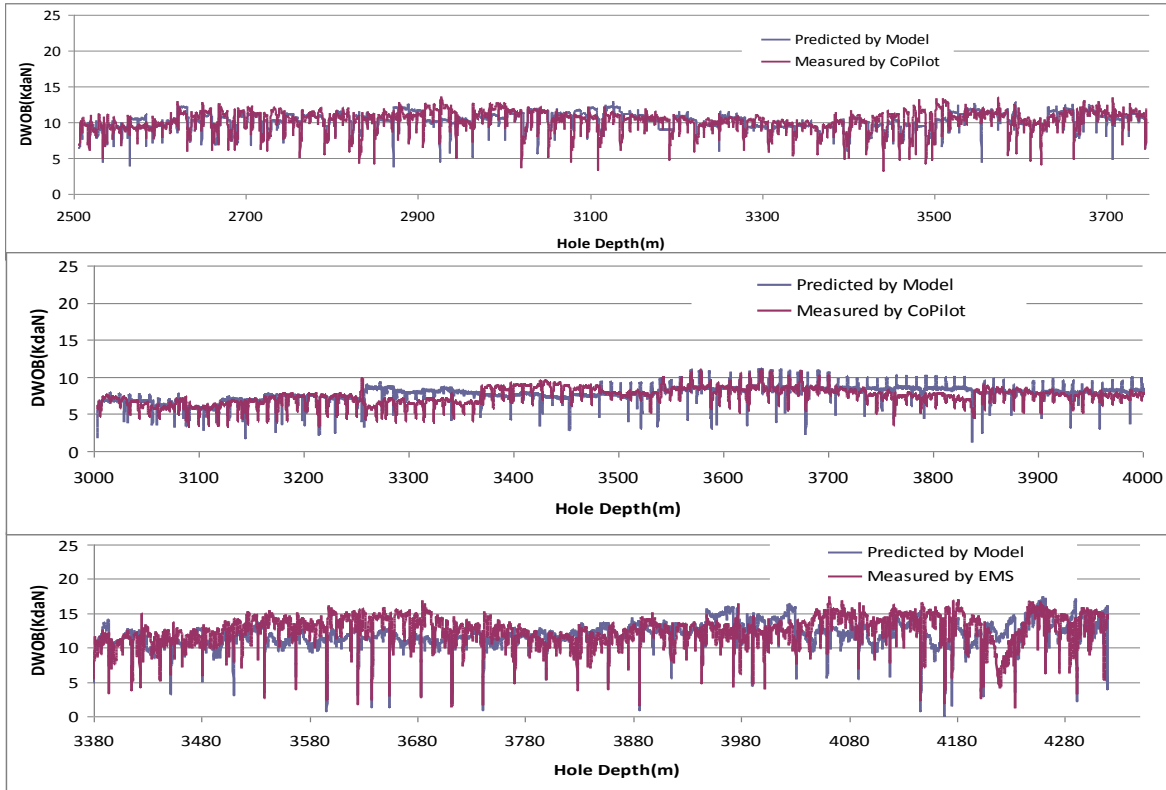


FIGURE 5. DWOB comparison between measured and calculated for the three wells

About the result of well#1, the DWOBs from model match those from the CoPilot very well in both the whole trend and values. However, there exist some minor differences in very small sections. These differences can be negligible. The prediction accuracy is over 80%, ϵ_{RMSE} or ϵ_{avg} . From the result of well#2, the DWOBs from model match those from the CoPilot in both the whole trend and values. There are some differences in three sections. The prediction accuracy is over 83% in ϵ_{avg} , and 75% in ϵ_{RMSE} . In the result of from well#3, the DWOBs from model match those from the EMS in both the whole trend and values. There are some differences in a few small sections. The prediction accuracy is close to 85% in ϵ_{avg} , and 80% in ϵ_{RMSE} . For the three wells, the average of ϵ_{RMSE} and ϵ_{avg} is around 80% and 86% respectively (as shown in table 1).

DEVIATION ANALYSIS AND IMPROVEMENT MEASURES

As discussed above there exist some deviations or differences between the measurement and the prediction. Potential reasons which caused those differences are discussed below.

For well#1, two deviation sources: one is from sliding mode, this deviation will be eliminated by using a correct model for sliding which is addressed in the next section. Another is the potential for measurement deviation which could be caused by the tool itself, or potentially because of the vibration of the drillstring.

For well#2, by checking the downhole measurement, it was found that the whirling severity diagnostic potentially had something to do with the difference. Another cause is probably

the wear of drill bit's gage section. When the drill bit is new, there are cutting force or friction applied on the gage section, and there is no force on the closer stabilizer. On the contrary, when gage section is worn out, the forces on the gage section decrease and some of them are transferred to the closer stabilizer. As the hookload is almost keeping the same, the predicted DWOB has the same trend as SWOB. However, the DWOB from CoPilot obviously decreased. Measurement deviation is a possible cause.

For well#3, it was found that when the predicted DWOB is maximum, the TTS hookload is minimum correspondingly. Therefore the possible reason is the lower TTS reading, or the lower reading was potentially caused by the vibration of the string.

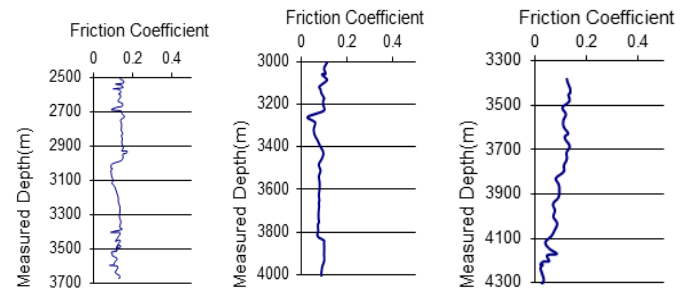


FIGURE 6. The friction coefficient calculated for the three wells

NEW SLIDING MODELING

From the previous analysis, some differences are from the

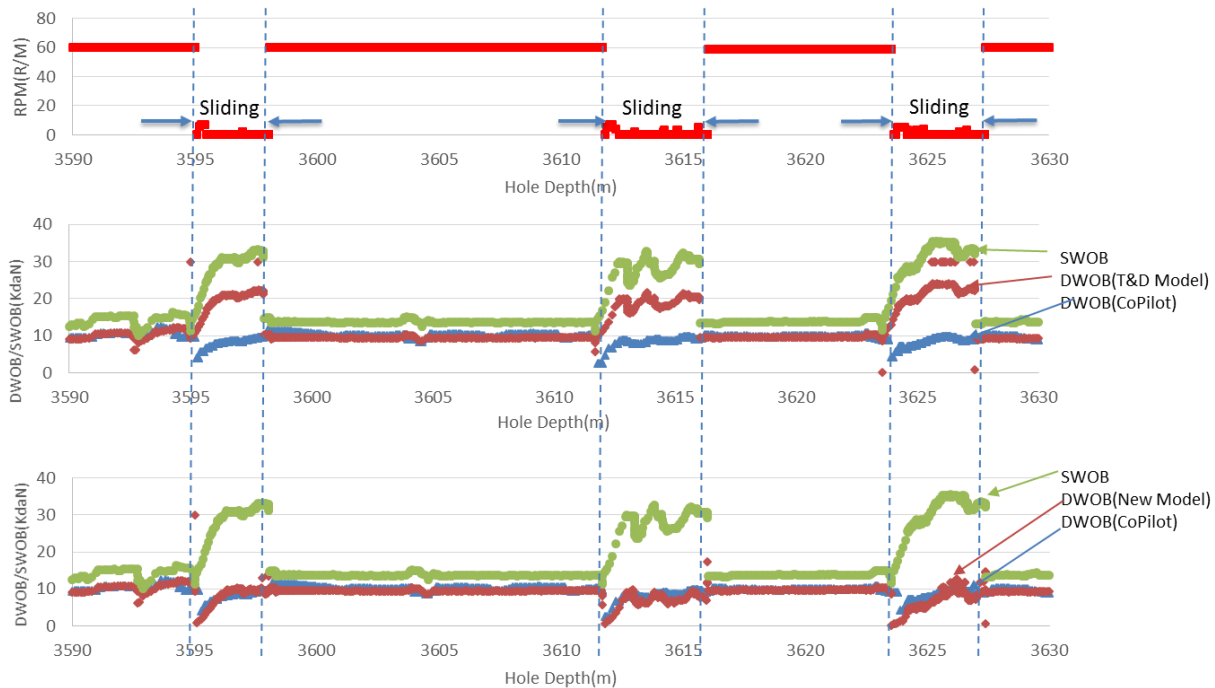


FIGURE 7. Comparison of DWOB/SWOB for three sliding sections

Comparison of DWOB/SWOB for All the Sliding Sections (2500m-3700m)

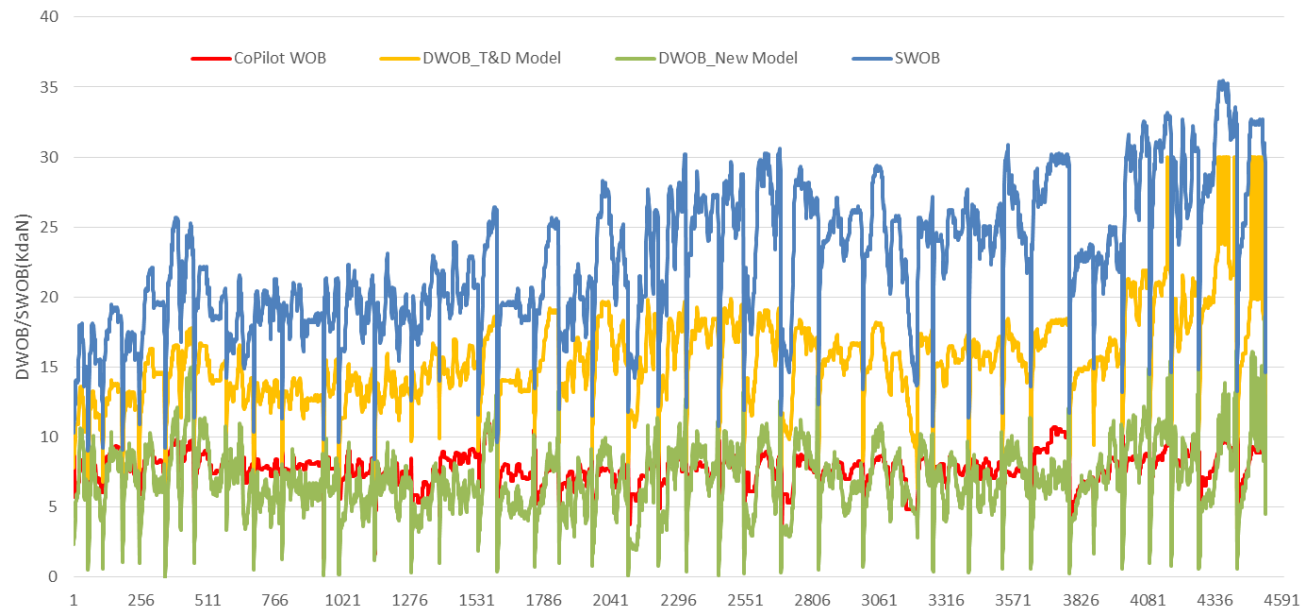


FIGURE 8. Comparison of DWOB/SWOB for all the Sliding Sections

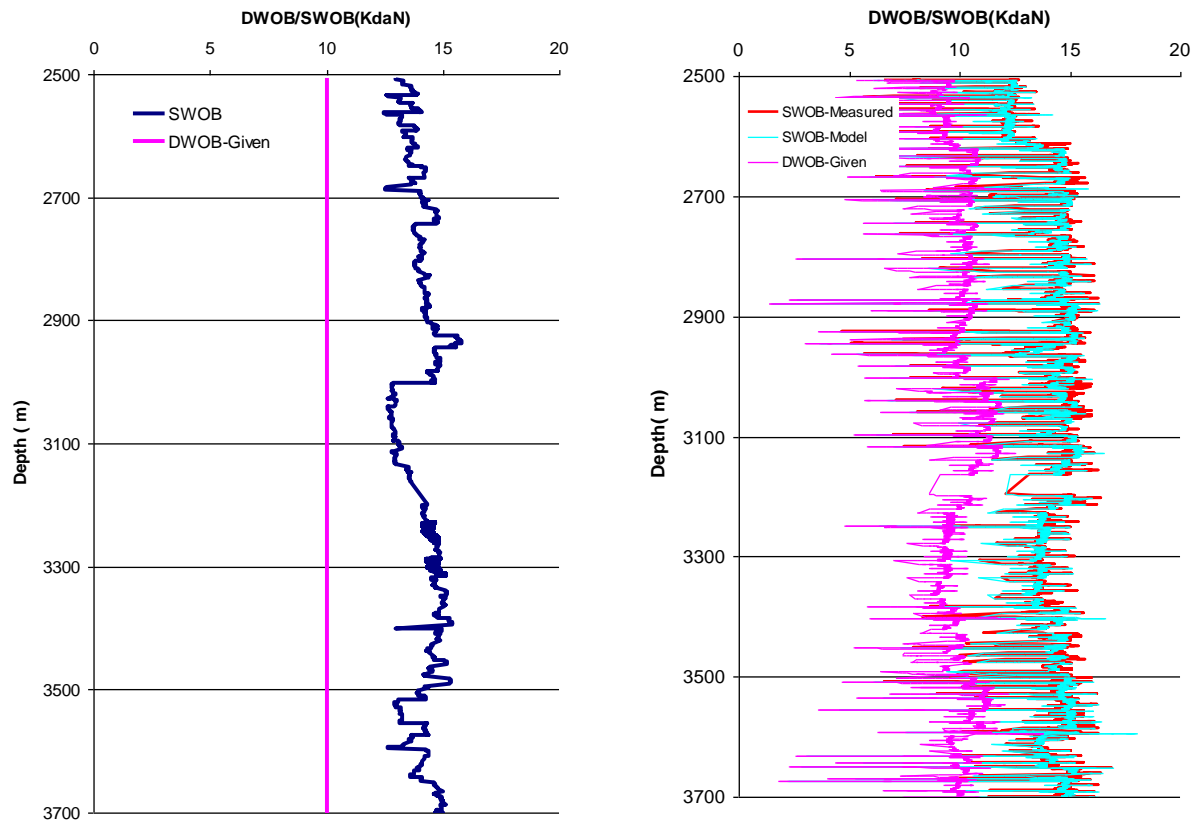


FIGURE 9. SWOB calculated given constant DWOB(left) and comparison of DWOB/SWOB(right)

model for sliding, therefore a new sliding modeling was developed. The T&D model did not work well in sliding mode as it is. It can be seen in figure 7 there is a big difference between the prediction and the measurement and it was therefore conducted more sliding modeling. It was seen that $DWOB_{sliding}$ is a function of differential pressure (DP), standpipe pressure, $DWOB_{rotation}$, and coefficient K related to motor type as shown in Eq. 9. $DWOB_{rotation}$ is obtained with T&D model, and K is obtained by comparing $DWOB_{rotation}$ to $DWOB$ from the measurement tools. With the new sliding model, there is a good match. Figure 7 shows the comparison of $DWOB/SWOB$ for three sliding sections. Figure 8 shows the comparison of $DWOB/SWOB$ for all the sliding sections.

$$DWOB_{sliding} = K \cdot \frac{DP}{SPP} \cdot DWOB_{rotation} \quad (9)$$

DWOB/SWOB AUTOMATION

From the previous sections, the new Autodriller can automatically calculate $DWOB$ by the use of surface drilling data. A key feature of this new type Autodriller is that it can also automatically get surface weight on bit if target $DWOB$ is given. If the $DWOB$ is fixed at a formation for a specific drill bit the $SWOB$ is automatically obtained with the new Autodriller software system as shown in figure 9(left). Figure 9 (right) shows the comparison of $DWOB/SWOB$ -Model/ $SWOB$ -Measured.

SUMMARY

The following conclusions can be drawn from the newly developed and verified Autodriller system.

1. A new concept is developed and presented that gives more accurate downhole WOB based on surface measurements.
2. The new modeling can be integrated in a new Autodriller system that gives accurate $DWOB$ predictions in horizontal wells using surface measurements.
3. Analyzing three horizontal wells, the verification results are very good in most of the horizontal well sections.
4. The matches are good in most sections of the horizontal well, both in trends and values. The trends include two aspects: one is proximity between predicted $DWOB$ and the measured one; the other is between predicted $DWOB$ and the measured $SWOB$.
5. In a normal condition, the new Autodriller model gives consistent results. Those differences between the predicted and the measured are most likely caused by abnormal conditions such as stick slip, whirling, tool wear, vibrations or other. This can be improved by using other alert/alarm software when the Autodriller is being used if applicable.
6. One of the concerns is using the sheave efficiency and weight of traveling block, in that we get the values through

repeated tuning when calibrating. However, the existence of TTS solves the uncertainty of sheave efficiency and traveling block weight.

From the above points, the new Autodriller model has been proven. More trial wells will be collected for the further verification. This new Autodriller will be a closed loop control system that automatically and in real-time adjusts $SWOB$ so that the $DWOB$ is accurate, which will directly improve the performance of drill bits, and decrease the cost of drilling, especially in directional well drilling. In addition, the Autodriller can also in real-time monitor the compression/tension in the drillstring to prevent buckling.

NOMENCLATURE

- F_i, F_{i+1} the tension or compression at top end and bottom end of element i, N
 T_i torque, N.m
 β_i buoyancy coefficient, dimensionless
 w_i unit weight of element, N/m
 ΔL_i length of element, m
 μ_i friction coefficient, dimensionless
 φ_i, φ_{i+1} azimuth at top end and bottom end of element i, rad
 θ_i dogleg angle, rad
 α_i, α_{i+1} inclination at top end and bottom end of element i, rad
 ε_{avg} average of all absolute ε_i
 ε_i relative error percentage, dimensionless
 ε_{RMSE} rooted mean square error, dimensionless

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