The impact of Soft Torque Technology on Drilling Performance

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Abstract
It has long been known that torsional stick-slip vibrations are detrimental to the progress and efficiency of drilling operations, and a common root cause for tool failures. Many different technologies and methods have been implemented to deal with this issue. One of these technologies aims to actively dampen these vibrations from surface. The best known example of this method is the Soft Torque Rotary System (STRS), originally developed by Shell in the early ‘90’s. Although initially very successful, the relative effectiveness of Soft Torque diminished with the emergence and popular growth of modern AC, digitally controlled rotary drives. In recent years the implementation of the original Soft Torque technology has been improved and this rejuvenated implementation is now rapidly being deployed on the Shell global rig fleet. In 2009, Qatar Shell was one of the first to use this new Soft Torque implementation for the Pearl GTL development wells. Gulf Drilling International, GDI, has also taken up this technology and installed it on their Al-Khor jack-up rig, currently on contract with Qatar Shell. The paper details the experience and improvements seen as a result of the STRS installed on this rig and also cover Shell’s global experience with these systems.

Motivation
In 2009, the IADC/SPE conducted industry surveys regarding prevalent drilling issues and the technologies needed and they concluded a high demand for stick-slip mitigation (Springett 2010). As a result of this survey, in 2010 the IADC Future Technology held a workshop in Houston dedicated to stick-slip mitigation. To highlight the severity of stick-slip, an example of the worst stick-slip case seen was a “24 second bit stall and a 1.4 second backward drill rotation”, which is as bad as someone driving his car forward and then suddenly shifting into reverse (Womer 2011).

Gulf Drilling International (GDI) was established in Qatar in 2004 as a joint venture between Qatar Petroleum and Japan Drilling Co. who come with more than 40 years of offshore experience. GDI started working with Qatar Shell in 2011 on an appraisal well campaign and
is still providing its services via the “Al-Khor” jack-up rig. Vibrations in all their forms: axial, lateral and torsional have been experienced by GDI. In terms of the impact that these vibrations have, some of which are due to stick-slip, the failures recorded and attributed to them are plenty. Top drive failures due to vibrations are very common in the industry. As an example, a major drilling contractor who had significant experience using top drives on their rig fleet conducted an analysis to find out where most of their rig downtime occurred. They found that 40% of all rig equipment failures were related to top drive failures (Fraser 2009). GDI have experienced and are currently experiencing TDS failures mainly as a result of vibration (axial/lateral/Torsional). Following a survey from January 2008 to November 2012, as illustrated in table 1, GDI identified that of the entire top drive related NPTs, 13% were due to heavy vibration drilling.

**Table 1: GDI Top Drive related NPTs:**

<table>
<thead>
<tr>
<th>Year</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of total NPT</td>
<td>5%</td>
<td>19%</td>
<td>1%</td>
<td>24%</td>
<td>16%</td>
</tr>
</tbody>
</table>

Across the GDI drilling fleet, top drive failures have been continuously observed. The recorded failures are described below:

- TDS Gooseneck parted connection and this led to a leakage
- TDS Rotating Link Adaptor (RLA) failure
- TDS Saver Sub had cracked and sheared off (figure 1):
  - While coring 6” hole on Al-Khor sister rig
  - Drillstring parted from 3 1/2” IF saver sub connection and hung on elevator but did not drop on the rig floor thus nobody was hurt but the floor men were wet with mud
  - Following a root cause analysis, failure was due to vibration experienced by the top drive during coring operations
- TDS Torque Wrench Pipe Gripper failure due to sheared bolts (figure 2 a & b):
  - While drilling 16” hole on Al-Khor sister rig
  - Bolt head cap screw on pipe handler rear jaw had sheared
  - String vibrations were observed
Figure 1: Top drive Saver Sub sheared off

Figure 2 (a): sheared bolts on TDS Gripper

- Sheared Bolts on jaw of PH-100 and Link Tilt cylinder:
  - In July 2011, top drive failed while drilling 16” hole on the Al-Khor sister rig.
  - Two bolts holding front Jaw of PH-100 parted
  - One bolt for pin stopper of link tilt cylinder also parted

Figure 2 (b): Sheared socket head cap screw & worn key
In addition to the top drive failures, another key problem faced is core jams and poor core recovery. One of the reasons behind core jams is torque fluctuations sometimes attributed to stick-slip on bottom. A sister rig to the Al-Khor attempted coring with 8 ½” core heads and after more than 5 attempts they were only able to cut an average of 27’ to 68’ with only 50% recovery rates. Subsequent attempts to core with 6” core heads yielded similar results.

To solve the issue of torsional vibrations and stick-slip, we have to first understand how they are formed.

**Fundamentals of stick-slip vibrations**

Torsional stick-slip vibrations in rotary drilling have been the subject of many studies and publications over the decades (see references 3 to 5). To explain the fundamentals of stick-slip vibrations in rotary drilling a basic mechanical model of a drilling system is introduced, illustrated in Figure 3. The main components in this drilling system are:

1. **The speed source.** This is the power source controlling the rotation of the rotary drive (called speed source because the only input it receives is the required RPM with no torque fluctuation considerations).

2. **The rotary drive.** In modern rigs this is commonly an electric top drive system. These top drive systems are capable of delivering high torque and are represented in this model as a body with rotational inertia, \( J_{TD} \) [kgm\(^2\)].

3. **The drill string**, consisting of two parts:
   a) The drill pipe, acting as the mechanical conduit to transfer the torque from the rotary drive to the bottom-hole assembly (BHA) and the bit. The drill pipe is acting as a torsional spring \( K_s \) [Nm/rad].
   b) The BHA and bit, represented in the model as a body with large rotational inertia, \( J_{BHA} \) [kgm\(^2\)].
The generally accepted root cause for stick-slip torsional oscillations in rotary drilling is the negative damping provided by non-linear friction effects between the wellbore and BHA/bit as illustrated in Figure 4. This graph shows the friction torque as function of rotational speed. Friction is always counteracting the motion, so for positive rotation speeds the friction torque is negative. Figure 4 shows that as long as the bit/BHA is rotating at a sufficiently high speed, it experiences dynamic friction torque $T_{DYN}$. But when the bit/BHA comes to a (near) standstill, the friction torque jumps up to the higher static friction torque $T_{STAT}$.

As the drill string starts to rotate from standstill, it has to counteract the static friction by twisting the drill pipe. Once enough torque is built up, the BHA is set in motion and experiences the smaller dynamic friction torque. Once the BHA “slips” free, the drill string behaves like a torsional pendulum, with the drill pipe as a torsional spring and the BHA as a large rotational inertia. Similar to any torsional pendulum that is suddenly excited, it will vibrate with its fundamental frequency. Without the friction effects discussed above, viscous
damping from the drilling mud and material damping in the drill pipe would dampen this vibration and eventually the BHA would be rotating at the constant surface speed. But the difference between the static and dynamic friction torque is actually providing “negative” damping to the system. If this negative damping is sufficient the vibration of the BHA will not attenuate, but instead will momentarily halt the rotation. At this point the friction jumps back to the static value and the cycle restarts. This cycle describes what is experienced as continuous and periodic stick-slip vibrations whilst drilling. Those stick-slip vibrations are detrimental to the drilling progress and drilling efficiency, and a common root cause for tool failures.

In summary, the root cause for continuous stick-slip in rotary drilling is the negative damping provided by the difference in static and dynamic friction torque at the BHA/bit. If this negative damping is greater than the other damping sources in the drilling system, the vibration of the BHA will not attenuate but the BHA will come to a complete stop again after initially breaking free, sometimes breaking free at very high revolutions per minute (RPM). If there would be more damping forces in the drilling system, the vibration of the BHA would be dampened sufficiently to avoid coming to a complete stop again and re-starting the stick-slip cycle.

From the basic model of a drilling system the fundamental frequency of the stick-slip cycle is now easily calculated to be the first torsional natural frequency of the drill string:

$$\omega_{\text{stick-slip}} = \frac{k_s}{\sqrt{J_{\text{BHA}}}} \left[ \text{rad/sec} \right]$$

Equation (1)

Where:

- $k_s$ is the drill pipe stiffness [Nm/rad]
- $J_{\text{BHA}}$ is the BHA inertia [kgm$^2$]

**Current Solutions for Stick-Slip**

There are numerous procedural methods that can be applied to reduce and mitigate the stick slip phenomena. To reduce the occurrences of stick-slip proper hole cleaning is required along with good control of the drilling parameters particularly the RPM and weight on bit (WOB). In terms of bottom-hole assembly and bit design, having better contact between the drill bit and the borehole walls and using a stiffer assembly is thought to decrease torsional vibrations. Regarding the detection of stick-slip, it is suggested that high frequency data acquisition tools configured to measure torsional vibrations perhaps at the collar should be
deployed as close to the source as possible (Womer 2011). The soft torque system is seen by many as a useful tool to reduce and mitigate stick-slip and throughout this paper we will discuss how the system works and its impact on the operations in Qatar.

**Fundamental principle of Soft Torque**

From the basic understanding of how continuous, periodic stick-slip develops it is a small step to understand the fundamental principle of Soft Torque. For that, let’s again consider the basic model of a drilling system, shown in Figure 5a. Note that the speed source is very stiff and provides no additional damping to the system. This is because the speed source has only RPM considerations and does not account for torque adjustments while it is fluctuating, unless a pre-set torque limit is reached. If the speed source was also able to cleverly limit the torque it applied to the string then the oscillation feedback could be avoided. This would thus add more damping to the drilling system, and the continuous stick-slip cycle can be prevented. Soft Torque aims to add apparent damping to the drilling system at surface, as illustrated in Figure 5b.

![Figure 5: Mechanical representation of a drilling system with and without Soft Torque](image)

The principle of active damping at surface with Soft Torque technology alters the stiff speed source such that it behaves like a (tuned) spring-damper, with damping value $c_f$ and stiffness value $k_f$. This is achieved by actively controlling the relation between the torque load to the rotary drive and speed of the drive. By making the rotary drive act like a spring-damper, in the rotational axis, it is now able to absorb energy from the drill string and prevent the BHA from decelerating to a complete stop. This is done by adding additional energy when it is
needed and less energy when it is not required. Speed variations of the BHA will be dampened out and the drill string as whole, drill pipe and BHA, will now rotate at lower torque fluctuations while varying the RPM around a set value and thus the downhole RPM will be more constant. The damping provided by Soft Torque can be optimized by tuning the damping value $c_f$ and stiffness value $k_f$ to the stick-slip frequency. Still, the Soft Torque can only add a finite amount of damping to the drilling system. If the negative damping from the friction effects at the BHA/bit exceeds the overall damping in the drilling system, stick-slip will persist even with Soft Torque engaged.

**Soft Torque implementation in the drilling industry**

Soft Torque was originally developed and rolled out in the early ‘90s by Shell and was licensed to third parties, making it available to the entire drilling industry. Although initially very successful the relative effectiveness of Soft Torque was found to diminish with the coming of modern, digitally controlled top drives. This created a gap between the STRS electronic interface and the AC units without significant effort being put to remodel the system for AC units; however the need for it persisted. In response to this demise, Shell initiated the rejuvenation of Soft Torque technology in 2008 by working closely with the service companies supplying the technology. The original analogue electronic version of Soft Torque was integrated into the digital speed control of a top drive. Since 2008 the technology has now been implemented on over 50 Shell rigs and the results have been impressive. The roll-out of the technology on the Shell global rig fleet is presented in figure 6.
Figure 6: Qualified Soft Torque installations in Shell

Application of Soft Torque in Qatar

1. Pearl Development Wells:

Qatar Shell drilled and completed its Pearl GTL development wells during an extended simultaneous operations campaign (Vos 2008). In this process the drilling was done in stages and the completions were conducted simultaneously. A lot of vibrations were being observed and bit damage was seen. Therefore, it was decided to install the Soft Torque Rotary System (STRS) on the rig. When the STRS system was installed on the rig only the last hole sections of 7 wells remained to be drilled. The relative benefits of the Soft Torque system were gauged by comparing the drilling performance of the last 7 wells with the previously drilled development wells. The main comparator is the percentage of stick-slip phenomena seen. As explained earlier, this stick-slip is our primary concern as the predominant source of drilling issues. It can be measured by the following formula:

\[ Stick - slip = \frac{\text{Torque}_{\text{max}} - \text{Torque}_{\text{min}}}{\text{Torque}_{\text{av}}} \]  

Equation (2)

This phenomenon occurs every 5-7 seconds and we used the mud logs which were recorded every 5 seconds to obtain the results. To compare the wells, we have to first give an idea of the location of these wells and the relative distances between them.
The Pearl wells are located in Qatar’s North field and they were drilled from two platforms 12 kilometers apart. Each well extends a maximum of 2 kilometers away from the wellhead. The properties of the formations drilled are roughly the same. This does not mean however that anomalies and heterogeneities are not observed.

To make sure that this was a controlled comparison, the drilling parameters were analyzed and average values for each were obtained. It can be seen that in general the wells before STRS and the ones after had similar drilling parameters as can be seen in table 2. In terms of rig top drive system no alterations were made other than the installation of the STRS system. Regarding the BHA design and the drill bit used they were more or less the same but when the STRS system was installed a newer design of the same bit was used. Table 2 shows the average values of the drilling parameters used in drilling before and after STRS installation.

**Table 2: Drilling parameters for wells with and without STRS (8 ½” Section)**

<table>
<thead>
<tr>
<th>Well #</th>
<th>Footage (ft)</th>
<th>ROP (ft/hr)</th>
<th>Bit RPM</th>
<th>Surf RPM</th>
<th>WOB (k-lbs)</th>
<th>Torque (k ft-lbs)</th>
<th>Stick Slip (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRS Installed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well L</td>
<td>3316</td>
<td>68</td>
<td>279</td>
<td>81</td>
<td>25</td>
<td>16 24 27</td>
<td>9</td>
</tr>
<tr>
<td>Well K</td>
<td>4035</td>
<td>69</td>
<td>263</td>
<td>79</td>
<td>29</td>
<td>20 23 26</td>
<td>8</td>
</tr>
<tr>
<td>Well J</td>
<td>3436</td>
<td>78</td>
<td>279</td>
<td>80</td>
<td>27</td>
<td>25 27 28</td>
<td>8</td>
</tr>
<tr>
<td>Well I</td>
<td>4136</td>
<td>76</td>
<td>280</td>
<td>84</td>
<td>29</td>
<td>19 24 27</td>
<td>9</td>
</tr>
<tr>
<td>Well H</td>
<td>4093</td>
<td>79</td>
<td>297</td>
<td>101</td>
<td>27</td>
<td>19 24 27</td>
<td>10</td>
</tr>
<tr>
<td>Well G</td>
<td>3614</td>
<td>93</td>
<td>264</td>
<td>74</td>
<td>26</td>
<td>19 22 25</td>
<td>11</td>
</tr>
<tr>
<td>No STRS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well F</td>
<td>3204</td>
<td>84</td>
<td>281</td>
<td>81</td>
<td>29</td>
<td>22 26 29</td>
<td>12</td>
</tr>
<tr>
<td>Well E</td>
<td>2535</td>
<td>59</td>
<td>303</td>
<td>101</td>
<td>32</td>
<td>17 27 30</td>
<td>15</td>
</tr>
<tr>
<td>Well D</td>
<td>2827</td>
<td>69</td>
<td>265</td>
<td>70</td>
<td>23</td>
<td>21 23 26</td>
<td>16</td>
</tr>
<tr>
<td>Well C</td>
<td>3079</td>
<td>36</td>
<td>305</td>
<td>103</td>
<td>21</td>
<td>23 27 29</td>
<td>10</td>
</tr>
<tr>
<td>Well B</td>
<td>2866</td>
<td>66</td>
<td>280</td>
<td>99</td>
<td>20</td>
<td>17 25 28</td>
<td>28</td>
</tr>
<tr>
<td>Well A</td>
<td>3088</td>
<td>43</td>
<td>288</td>
<td>97</td>
<td>22</td>
<td>16 20 22</td>
<td>8</td>
</tr>
</tbody>
</table>

The stick-slip was calculated in 5 second intervals for the wells with STRS enabled and compared with 6 wells drilled just before the installation of the STRS. The stick slip was then averaged for each well and a bar chart, figure 7, illustrates the differences of before and after enabling STRS. The STRS was installed in September on Well G and it was operational from then onwards until the completion of the campaign.
Figure 7: Stick-Slip percentage in wells with and without Soft Torque

It can be clearly seen that beginning with the installation of the STRS on Well G that the stick-slip phenomena was reduced and remained lower in all the succeeding wells. This illustrates that the soft torque system had achieved its objective in reducing the stick slip and in thus reducing the torsional vibrations and some of the problems associated with that. When torsional vibrations are mitigated, the energy that was dissipated on the stick-slip is now used more efficiently in drilling. This can be clearly seen reflected in the ROP rates when comparing before and after the system was installed as can be seen in figure 8.
Similar to the previous graph showing the stick-slip mitigation, an obvious ROP increase is visible from when the soft torque system was installed when comparing it to the previous wells. The percentage improvements in both ROP and in stick-slip after the STRS was installed are 30% and 41% respectively as can be seen in table 3.

Table 3: Stick-Slip and ROP percentage improvement with and without Soft Torque

<table>
<thead>
<tr>
<th></th>
<th>ROP (ft/hr)</th>
<th>Stick-Slip (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With-Out STRS</td>
<td>59.5</td>
<td>14.9</td>
</tr>
<tr>
<td>With STRS</td>
<td>77.2</td>
<td>8.9</td>
</tr>
<tr>
<td>% Improvement</td>
<td>29.7</td>
<td>40.6</td>
</tr>
</tbody>
</table>

Torsional vibrations are a significant cause of damage to the BHA and to the bit itself. To quantify the effect of STRS on bit damage, the IADC bit wear code was used. Records from all the bit wear were analyzed and the average damage to the inner and outer teeth of the PDC bits was quantified. This measurement is subjective but the same crew analyzed all the used bits which should provide some consistency in the values provided. Another factor to mention here is that the weighted average was taken for the bit wear with respect to footage.
drilled since not all the bits drilled the same amount. Table 4 illustrates the average number of feet drilled per bit and the average amount of wear seen on the bits. An improvement of around 200 feet per bit was seen before it had to be pulled out and a reduction in the teeth wear of around 35%.

Table 4: Footage per bit and bit wear with and without Soft Torque

<table>
<thead>
<tr>
<th></th>
<th>feet/bit</th>
<th>Bit Wear</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inner Teeth</td>
<td>Outer Teeth</td>
<td></td>
</tr>
<tr>
<td>With-Out STRS</td>
<td>2371.9</td>
<td>1.5</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>With STRS</td>
<td>2567.6</td>
<td>1.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>% Improvement</td>
<td>8.2</td>
<td>34.2</td>
<td>37.1</td>
<td></td>
</tr>
</tbody>
</table>

2. Appraisal Wells:
During the appraisal campaign, the Al-Khor rig witnessed top drive failure in the top hole section at a depth below 500 ft. The soft torque system was not switched on at that time since it is not very effective at depths shallower than 1000 ft. This means that the STRS would not have been able to prevent such an occurrence. However, the biggest impact GDI has seen due to the installation of the STRS system on the Al-Khor rig is the improvement in coring and the reduction in core jams. A critical requirement of any appraisal well is to obtain high quality cores with high recoveries and minimal damage. As mentioned earlier, vibrations and stick slip are some of the reasons behind core jams. This is where the soft torque system kicks in and mitigates the stick-slip thus reducing the torque fluctuations and minimizing damage to the cores.

On the first appraisal well, the ratio of the cumulative length of core retrieved to the cumulative length of core barrels ran in hole was 70 % with a core recovery of 99.5% with the longest core being 482 ft. On the second appraisal well, the ratio was 65% with a core recovery of 95.8% with the longest core being 480 ft. As seen from these numbers, there is some consistency with the efficiency of the coring process. On the other hand, when we compare the cores retrieved from these two wells with cores retrieved using a sister rig to the Al-Khor we see a visible difference.

To establish the comparison the differences and similarities in rig design have to be acknowledged. The two rigs are identical in design and in the top drive system but Al-Khor is equipped with the STRS. In terms of the location, the 2 rigs operate in the same field but this does not necessarily imply the same formation depths, thicknesses or strengths but more or less similar. The coring heads used where of different brands and different sizes, 8 ½” and
6’’ on the other rig, and these are the main differences in this comparison that we are unable to account for. However, the drilling parameters used were similar with Al-Khor having a slightly higher WOB and a slightly higher ROP.

On the sister rig, the ratio of the cumulative length of core retrieved to the cumulative length of core barrels ran in hole was merely 40.9 %. As mentioned earlier, there is more than one factor in this comparison that are not controlled but STRS was a member of these factors that contributed to a higher ratio on Al-Khor rig. Table 5 summarizes the comparison between the three wells.

**Table 5: Comparison of core retrieved between 2 wells on Al-Khor and a sister rig**

<table>
<thead>
<tr>
<th>Well Name</th>
<th>STRS Installed</th>
<th>Cored interval/Core Barrel (%)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appraisal Well 1</td>
<td>Yes</td>
<td>70.4</td>
<td>99.5</td>
</tr>
<tr>
<td>Appraisal Well 2</td>
<td>Yes</td>
<td>65.2</td>
<td>95.8</td>
</tr>
<tr>
<td>Sister Rig</td>
<td>No</td>
<td>40.9</td>
<td>-</td>
</tr>
</tbody>
</table>

Looking at the cores taken in more detail, an analysis of the torque response chart had to be made. Looking at two cores from the same interval one from Appraisal Well 2 and the second from the sister rig, we can clearly see a difference in the torque reading and the RPM response. Figure 9.a was obtained from the sister rig coring operations and the fluctuations of the torque readings appear to be very high, while the RPM was held constant. To enable a performance comparison, a log of coring on Al-Khor at the same formation interval was selected. The Al-Khor core has a lot less torque fluctuations and minor RPM variations to reduce the stick slip effect, figure 9.b. To observe and analyze how the STRS system is operating and reducing the torque, we collected high frequency data from the STRS system every 50 milliseconds. This data is recorded by the system and needs to be extracted and analyzed.

The two red circles on figure 9.b are zoomed out and magnified in the high frequency STRS data. These two intervals were highlighted because they clearly show how the STRS mitigates the torque fluctuations in Figures 10 and 11. As soon as the system detects rapid and drastic fluctuations in the measured surface torque, it responds by varying the surface RPM to dampen the torsional vibrations generated. This immediate reduction of the continuous torque fluctuations aids in preventing the core jams and in a more efficient use of the energy.
Figure 9: Torque Response while coring from

a) sister rig b) Al-Khor
Figure 10: RPM adjustment to reduce torque in 1st red circle

Figure 11: RPM adjustment to reduce torque in 2nd red circle
Conclusions

The Soft Torque Rotary System has aided Qatar Shell in achieving its drilling performance objectives, saving costs and acquiring better cores. The Pearl Development Campaign witnessed a 30% increase in ROP, a 41% reduction in stick-slip phenomena and 35% less damage to the bit teeth in the 8 ½” hole section. For the appraisal wells, GDI utilized the STRS system in its drilling and coring operations. In terms of top drive and drillstring failures which are revenue loss related, the Al-Khor has less failure due to stick slip or heavy vibration drilling when compared with the sister rig. GDI has observed performance benefits over their sister rig which was also coring in a similar field but with a lower success rate. When comparing the torque readings between the two rigs while coring, there was evidence that Al-Khor had lower torque values and lower fluctuations which can be linked to the dampening effect of the STRS. It was also possible to witness the soft torque system in action and how it was able to vary the RPM to reduce the torque fluctuations.

Acknowledgements

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