Optimized Hummingbird control curve in EP AST 2.1 soft torque system applied to drilling a horizontal well section between 18000ft and 35000ft

1. Introduction

AST 2.1 soft torque system is Electroproject's (EP) newest implementation of soft torque technology. This technology aims to resolve (mitigate) the negative effects of the frequently arising stick-slip phenomena in oil and gas well drilling. To do this the rotation dynamics of the (top)drive in the drilling rig is changed. This can be expressed by the so-called "hummingbird control curve", showing drive damping characteristics over frequency which dictates the relation between the drive's rotation speed and torque.

AST 2.1 is the new generation soft torque controller. AST 2.1 finds its strength in:
- Wide control frequency band to allow damping of all relevant torsion vibration modes of the drill string. This obviates the need to re-tune at different drilling depth. Only in difficult cases such as drilling horizontal and deep wells, the "hummingbird control curve" of AST 2.1 should be optimized to include the effects of the specific well and drill string geometry.
- Optimizations to minimize the downhole (Bit/BHA) speed fluctuations. Specially useful for directional drilling operations.

This document shows a prediction of AST 2.1 capacity to mitigate stick-slip and how it compares to the conventional STRS implementation for drilling a challenging horizontal well (by making use of an advanced drill string model). The results are shown for two different 35000ft long drill string configurations: a **tapered** drill string (String-1) and a **non-tapered** drill string (String-2). Also, the effect of the mass moment of inertia of the (top) drive is shown.

2. The rotation dynamics of the drill string and stick-slip mitigation

The drill string forms the connection between the (top)drive in the drilling rig and the bit/BHA downhole. Stick-slip mitigation requires to keep the rotation speed of the bit/BHA end of the drill string as constant as possible i.e. zero or minimal speed fluctuations.
Conventional (top)drive control systems are designed to maintain a requested (driller's) drill string rotation speed independent of the (torque) load from the drill string and bit, under the false assumption that the bit/BHA rotation speed is always identical to that (visible) on the rig.
In reality, however, the drill string forms a flexible mechanical vibration system whereby, under circumstances, high bit/BHA speed variations can exist, leading to stick-slip in which the bit/BHA intermittently comes to a complete stall.

3. The way soft torque systems work

The above translates into the basic requirement for modern stick-slip mitigation:

How to adapt the (top) drive speed control system to minimize the bit/BHA speed variation under various (torque) load conditions?

To answer this question, we need to understand the nature of rotation vibrations of the drill string. This can be done by realizing that the torsion vibration is composed of a number of vibration modes (each with a distinct vibration frequency). Depending on drill string geometry, (top) drive behavior and loading one or more of such vibration modes may be more apparent than others, resulting in a specific speed and torque pattern along the length of the drill string.

A vibration mode may be damped by extracting its vibration energy. The top drive control system is the obvious instrument to do this. By allowing the speed control system some softening (i.e. speed variation) at the frequency of a particular vibration mode, it can be proven that vibration energy of that mode can be extracted (i.e. dissipated). This will then reduce or remove the particular vibration mode.

The conventional STRS (EPST) system is designed to focus only on the first mode (with the lowest frequency). Since the vibration frequency of the modes changes with depth STRS needed to be re-tuned after drilling every stand.

The advanced AST 2.1, however, is designed to focus on all vibration modes at the same time by means of its wide frequency band. The capacity of extracting vibration energy of a (top)drive over frequency is expressed by the “hummingbird control curve” of the respective soft torque system (see blue line in figure 1 and 2). The Y-axis is formed by a normalized power scale:

$$y\_value = 1 - normalized\ TD\ dissipation\ power \qquad [-]$$

And the X-axis is formed by the torsion vibration frequency of a mode in [Hz].

The “hummingbird curve” thus indicates how much a vibration mode reaching the (top)drive can be dissipated by the (top)drive as a function of the mode frequency. This means that dissipation power is positive if y_value is smaller than 1 and negative if y_{value} is larger than 1 (please note: the name “hummingbird” originates in the fact that the advanced soft torque control curves look very similar to the shape of a Hummingbird bird).

Top drives and their control systems reveal certain limitations (e.g. the magnitude of the mass moment of inertia and delays in the control system) which make it more difficult to damp a vibration mode at higher frequencies due to the decreasing stability of the (top) drive at those frequencies. In fact, a vibration mode is even amplified by the (top) drive in case its frequency coincides with the frequency of the “head” in the “hummingbird curve” (y_{value} > 1). Therefore, AST 2.1 contains special developed techniques to minimize the effects of such limitations while guarantying safe stability margins of the (top)drive. They can be expressed by stability curves (System Sensitivity (red) and Noise Sensitivity (cyan)) together with the hummingbird curve (blue) (see figures 1 and 2).

4. Characterization of stick-slip mitigation capacity of soft torque systems

Since it is important to minimize the bit/BHA speed variation, we need a (computable) indicator to express the mitigation capacity under various drilling circumstances. It can be proven that the (top)drive control system together with the dynamics of the drill string results, for each vibration mode, in a damping marge at bit/BHA. This can be seen as the amount of (positive) damping which is available at the bit/BHA for that vibration mode. The actual drilling loading process may under circumstances "produce" a negative damping magnitude. It can also be proven, that in case the **sum of the drilling system damping marge and the negative damping of the loading process** becomes negative, that vibration mode will become instable, i.e. that mode turns into stick-slip. From this mechanism we can derive following stick-slip mitigation strategies:

a. ***Controlling the respective soft torque system*** to maximize the bit damping marge for all vibration modes. The mode with the smallest damping marge will be the most critical one. AST 2.1 uses an optimization technique (based on models of both the (top) drive and the drill string) to maximize the critical damping marge while guarantying acceptable (top) drive stability margins.
b. ***Influencing the drilling loading process***. The operational parameters such as RPM, WOB and formation friction characteristics dictates the loading process. In general, increasing the RPM and reducing the WOB will reduce the effective negative damping and therefore reduce the tendency to get into stick-slip. Although this effect is difficult to quantify (since variable formation friction characteristics are involved) it can explain why when using a good soft torque system drilling can be done with lower RPM and more importantly with higher WOB resulting in potential higher ROP.

5. AST 2.1 case study

Based on the above described methodology we are able to compare the mitigation capacity of drilling a challenging horizontal well up to 35000ft. For this we use following assumptions:

Horizontal well section from 18000ft to 35000ft.

String1 (**tapered**) drill string geometry:
- 145ft 6 ¾" BHA
- 280ft 5" HWDP
- 13120ft 5" DP (19.5 lbs/ft)
- 4575ft 5 7/8" DP (23.4 lbs/ft) @ depth = 18000ft
- 21575ft 5 7/8" DP (23.4 lbs/ft) @ depth = 35000ft

String2 (**non-tapered**) drill string geometry:
- 145ft 6 ¾" BHA
- 17855ft 5 ½" DP (21.9 lbs/ft) @ depth = 18000ft
- 34855ft 5 ½" DP (21.9 lbs/ft) @ depth = 35000ft

Top drive:
- Mass moment of Inertia = 1000 [kgm^2] and 2200 [kgm^2]
- Delay in top drive control system ~5ms

6. Comparison results for STRS (EPST) with optimized AST 2.1 control parameters using tapered and non-tapered drill string

6.1. Hummingbird control curves

Figure 1 and 2 show the optimized AST 2.1 hummingbird curves (blue) for the tapered (String1) and the non-tapered (String2) drill strings. Both curves are optimized over the entire (17000ft) hole section, together with acceptable top drive stability curves (red: system sensitivity and cyan: noise sensitivity). The (tuned) hummingbirds (black lines) of the conventional STRS system are shown here for comparison.

Comparing figure 1 (tapered) with figure 2 (non-tapered) it appears that the optimization process results in a less aggressive curve when using the non-tapered drill string.

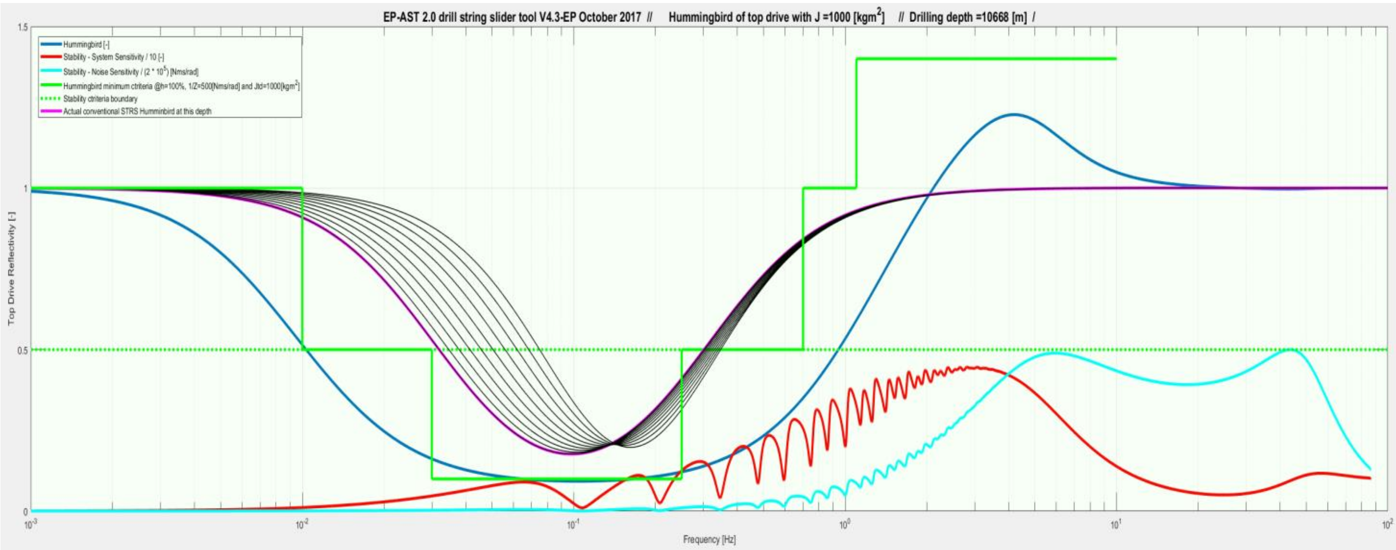

Figure 1: Optimized hummingbird control curve ***for String1 (tapered)*** *from 18000ft to 35000ft (blue curve)*

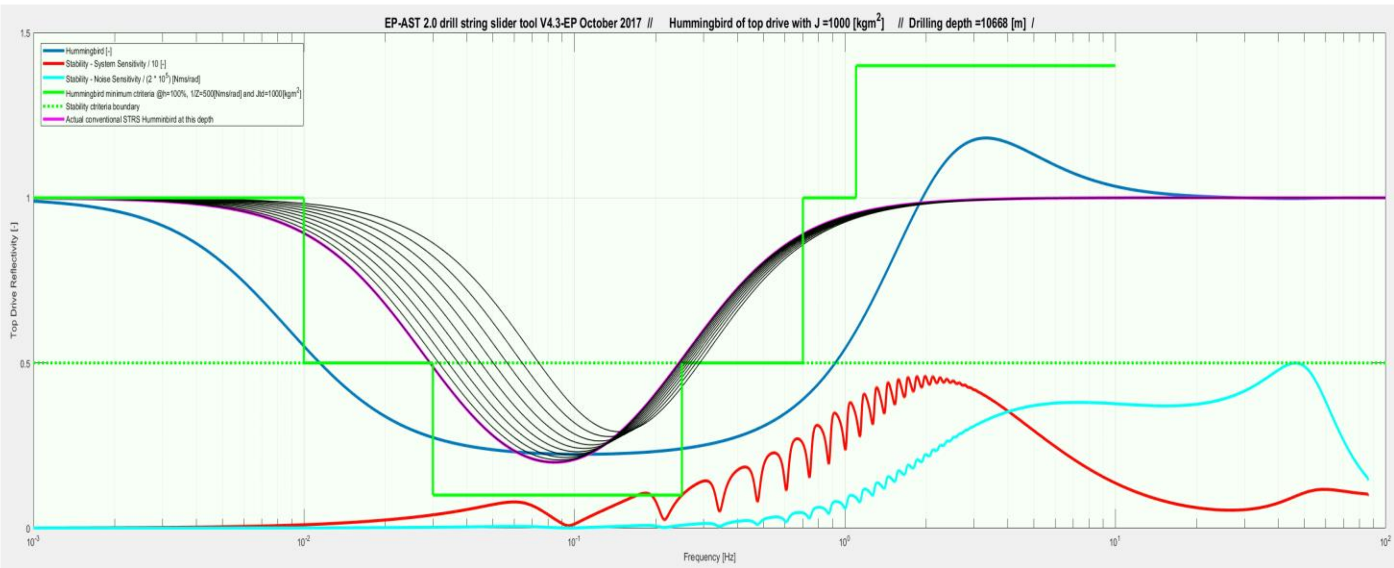

Figure 2: Optimized hummingbird control curve ***for String2 (non-tapered)*** *from 18000ft to 35000ft (blue curve)*

6.2. Downhole damping marges

More importantly we are interested in the achievable damping marges at the bit/BHA for all (relevant) torsion vibration modes.

Based on the shown AST 2.1 optimized hummingbird curves, figure 3 (tapered drill string) and figure 4 (non-tapered) compare the achievable damping marges at the bit @ 35000ft (green and red sticks). The dotted magenta lines in both figures show the changes from 18000ft to 35000ft for the first five (relevant) drill string vibration modes (as indicated for the first mode by the yellow labels).

Note: The resulting achievable damping marge at the bit provides an indication for the stability of a torsion vibration mode while drilling. The larger this value, the less chance of developing an instable mode which may lead to **stick-slip** (see also section 4 above).

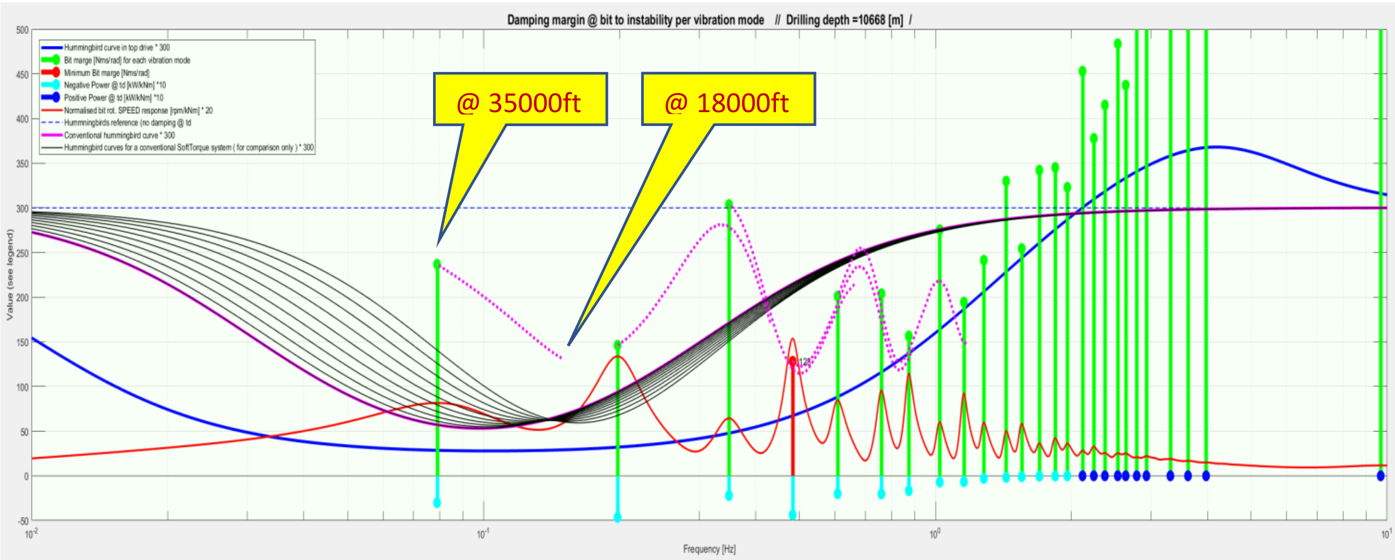

*Figure 3: The achievable damping marge **for the tapered drill string** for each torsion mode (green sticks) versus normalized rotation speed (red curve) at the bit*

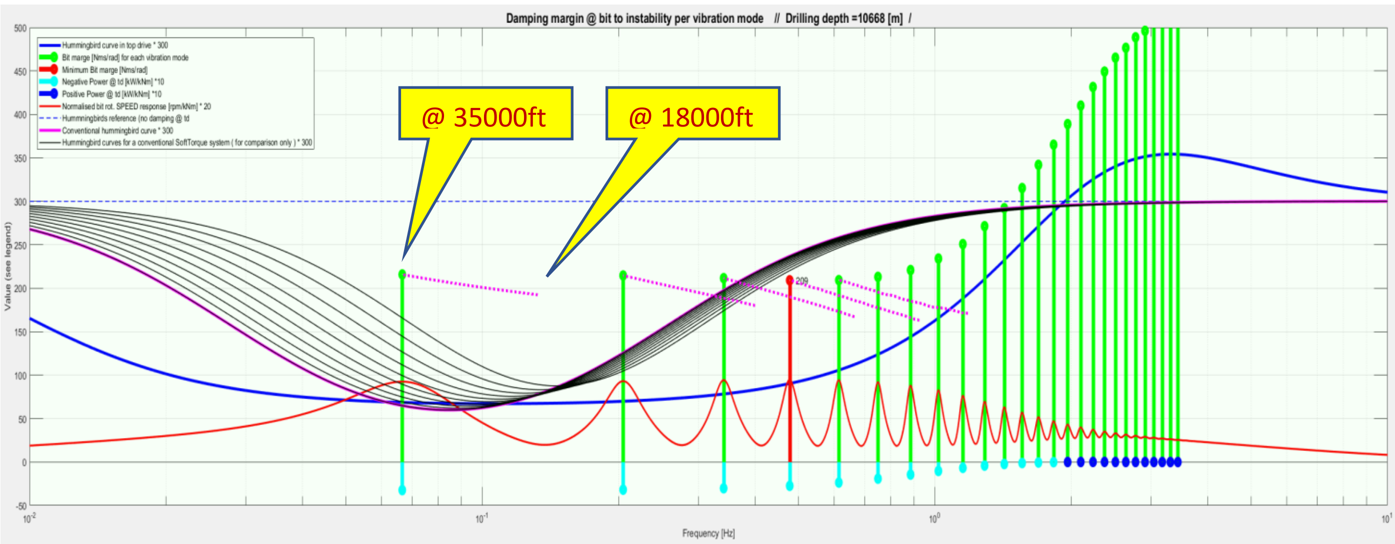

*Figure 4: The achievable damping marge **for non tapered drill string** for each torsion mode (green sticks) versus normalized rotation speed (red curve) at the bit*

It is clear that at 35000ft the 4th mode (=red stick) appears to be dominating in both cases. Comparing figure 3 with figure 4, it appears that while using a non-tapered drill string the damping marge for the various vibration modes are much more balanced and on average ~40% larger than using a tapered drill string. Also, the change in damping marge while drilling the hole interval from 18000ft to 35000ft is much smoother in the case of using a non-tapered drill string (figure 4).

6.3. Normalized (rotation) speed pattern along the drill string

Comparison of the (normalized) rotation speed variation of the critical 4th mode (red sticks in figures 3 and 4) along the drill string show a clear (~40%) improvement when using the non-tapered drill string.

Please note the amplification in the speed amplitude at the drill string tapering point (transition from 5 7/8" DP to 5" DP) is completely vanished in figure 6).

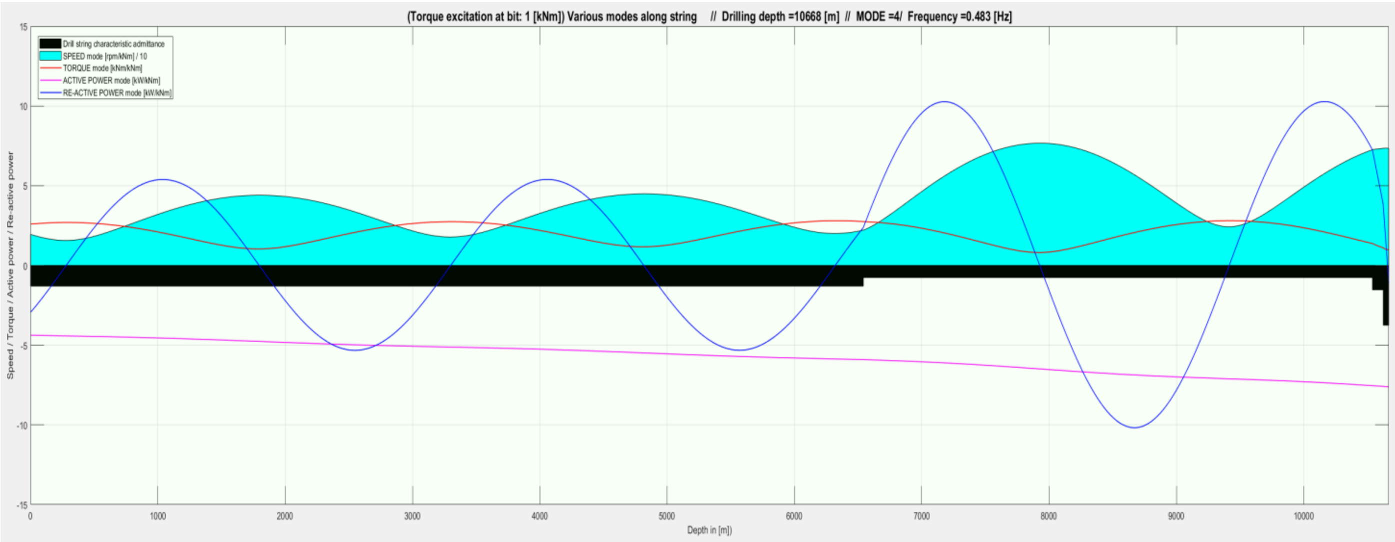

*Figure 5: The most domination torsion vibration mode (4th) **for tapered drill string** in this hole interval*

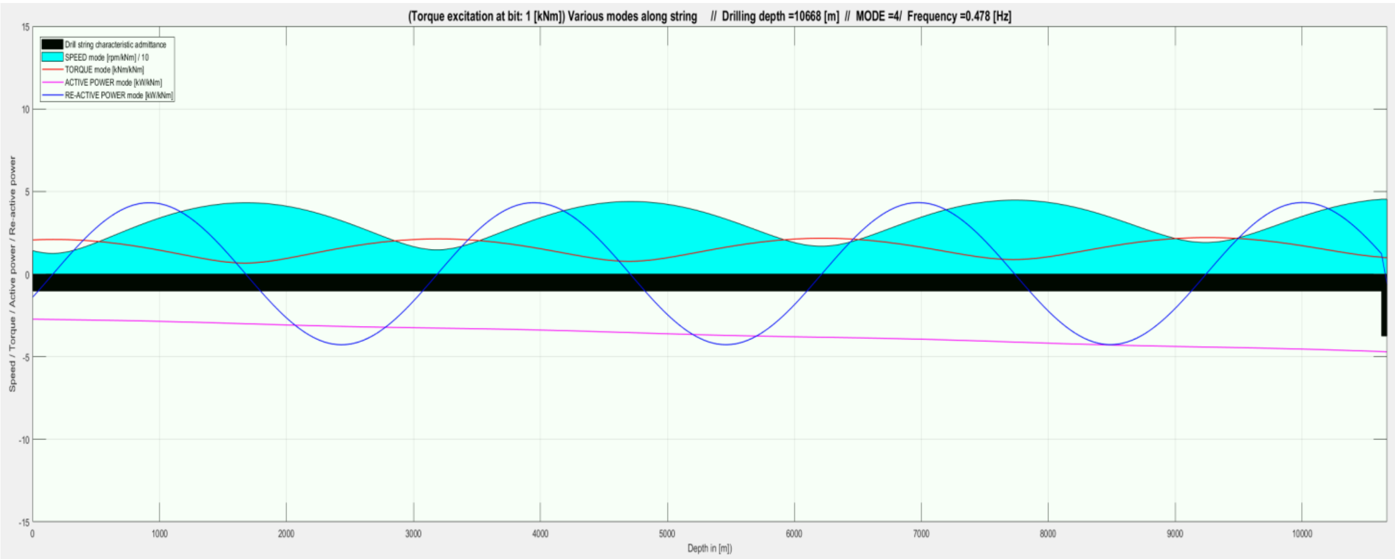

*Figure 6: The most domination torsion vibration mode (4th) **for non-tapered drill string** in this hole interval*

6.4. Critical damping marges

If we now use the minimum (=critical) bit marge (red stick) as a measure for mitigation capacity we can construct the graph in figure 7. Here we compare such critical values over depth for different soft torque systems:

a. Soft torque system is OFF (blue lines)
b. Soft Torque system is conventional (STRS or EPST) (red lines)
c. Soft torque system is new AST 2.1 (magenta lines)

Where dashed lines represent the tapered drill string case (String 1) and continuous lines represents the non-tapered case (String 2).

It is clear that AST 2.1 outperforms STR (EPST) but also that the drill string composition (tapered versus non-tapered) has a large effect on the stick-slip mitigation capacity.

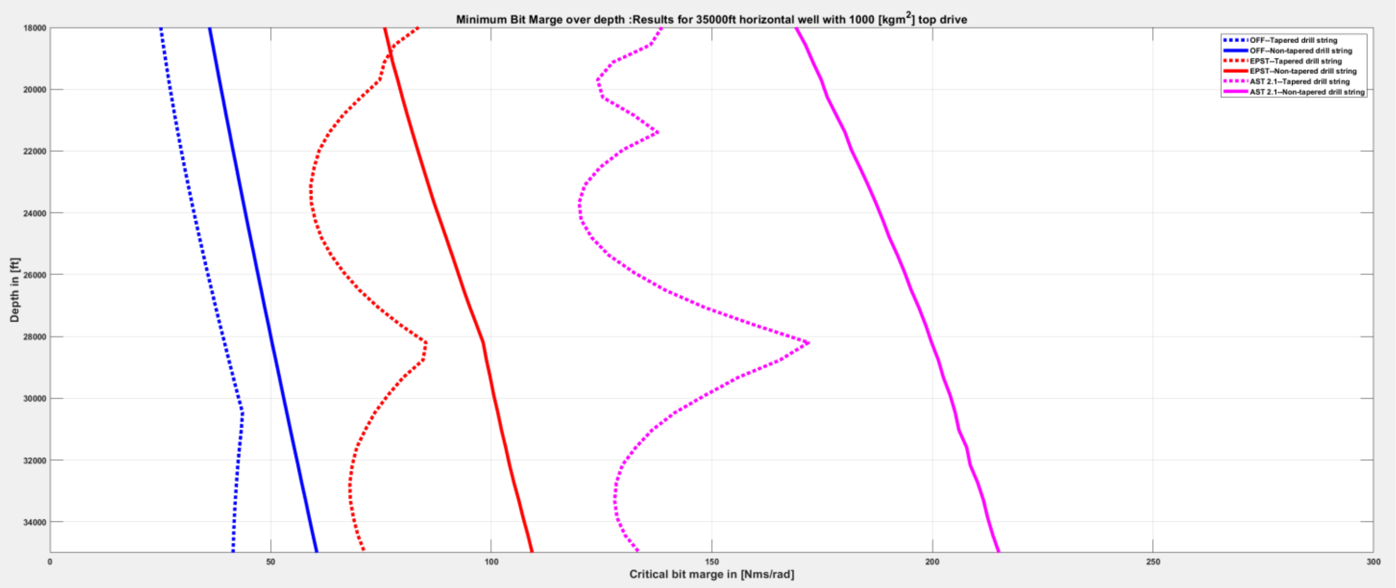

*Figure 7: Comparison between various soft torque systems and drill string configuration for (top) drive inertia of **1000** [kgm^2]*

6.5. Influence of the mass moment of inertia of the (top) drive

An important property of the drilling system is the (mass moment of) inertia of the (top) drive. The larger this (physical) value the more it limits the capacity to damp vibration modes in particular at higher frequencies.

Figure 8 shows the same cases as presented in figure 7 but with a much higher inertia of 2200 [kgm^2].

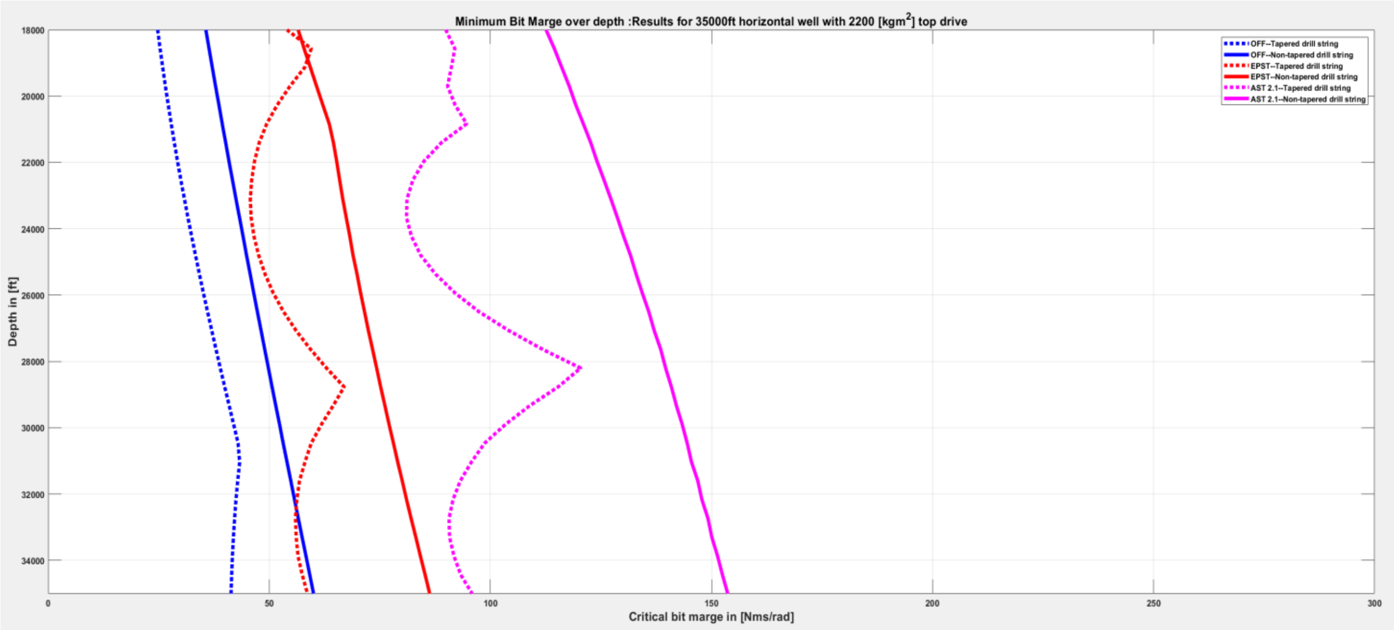

*Figure 8: Comparison between various soft torque systems and drill string configuration for (top) drive inertia of **2200** [kgm^2]*

7. Conclusions

1. The AST 2.1 soft torque system can be optimized to achieve a maximum damping marge for all relevant vibration modes in this horizontal hole interval. This will minimize the chance of developing stick-slip for all the vibration modes in a balanced way.
2. The AST 2.1 soft torque system outperforms in all cases the conventional STRS (EPST) soft torque system. It roughly doubles the achievable critical bit/BHA damping marge.
3. Improvements of using a **non-tapered drill string** over using a **tapered drill** string are clear:
   - Hummingbird control curve can be less aggressive
   - Damping marge at bit of the vibration modes are much more balanced and increase slightly proportional with depth while drilling from 18000ft to 35000ft.
   - The speed vibration magnitudes at the bit/BHA are on average about ~40% smaller.
   - All vibration modes get smaller with depth.
4. Although the above still does not give a guarantee to mitigate all possible stick-slip events, in general more aggressive drilling parameters (RPM and WOB) may be chosen (and consequently resulting in higher ROP) before running into stick-slip.
5. The actual downhole velocity weakening friction behavior will in the end determine whether stick-slip develops. This is highly influenced by the drilling operating conditions (RPM, WOB) and formation friction properties.
6. Further improvements may be realized by automatic and more frequent optimization (e.g. at regular depth intervals) of the AST 2.1 control system.
7. The given (physical) mass moment of inertia of the (top) drive has a large effect to the mitigation capacity of soft torque systems.