INVESTIGATING THE DRCAT ALGORITHM AS A SOLUTION TO AUTO-DRILLER DYSFUNCTION AND AUTOMATIC TUNING

A Thesis

by

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ABSTRACT

The effect of auto-driller behavior has started to more attention in literature (Pastusek et al. 2016). Dysfunction can occur when the bit transitions to a harder formation and if the control gain of the auto-driller's P.I.D. controller is not adjusted, then instability in the system can occur. An algorithm has been tested as a solution to adjusting this control gain in real time (Badgwell et al. 2018). The behavior of the algorithm is as the authors desired when WOB mode is active for extended periods of time. When it is not, such as in shallow, surface drilling, then the algorithm has its fallbacks when it comes to increasing the control gain over time. On simulated data, there is significant improvement in the drum rotation speed of the drawworks, in terms of stability. There could be positive results for lateral drilling, but issues with weight transfer to the bit bring these into question.

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Contributors

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NOMENCLATURE

delta P	Differential Pressure
Dia	Bit Diameter
DOC	Depth-of-Cut
K or P_{gain}	Control Gain
MSE	Mechanical Specific Energy
P.I.D.	Proportional – Integral – Derivative
ROP	Rate of Penetration
T_d	Derivative Time
T_i	Integral Time
TOR	Torque
WOB	Weight-on-bit

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1. INTRODUCTION

1.1. Introduction

The effect of auto-driller behavior has started to more attention in literature (Pastusek et al. 2016). Dysfunction can occur when the bit transitions to a harder formation and if the control gain of the auto-driller's P.I.D. controller is not adjusted, then instability in the system can occur. An algorithm has been tested as a solution to adjusting this control gain in real time (Badgwell et al. 2018). The behavior of the algorithm is as the authors desired when WOB mode is active for extended periods of time. When it is not, such as in shallow, surface drilling, then the algorithm has its fallbacks when it comes to increasing the control gain over time. On simulated data, there is significant improvement in the drum rotation speed of the drawworks, in terms of stability. There could be positive results for lateral drilling, but issues with weight transfer to the bit bring these into question.

1.2. P.I.D. Control

The most common method of controlling processes is through Proportional-Integral-Derivative control, or P.I.D. control. The vast majority of feedback loops employ this algorithm in one way or another. The objective of the feedback loop is to increase the manipulated variable when the process variable is smaller than the set point and decrease the manipulated variable when the process variable is larger than the set point. A block diagram of a process that employs a feedback controller is shown in **Fig. 1**:

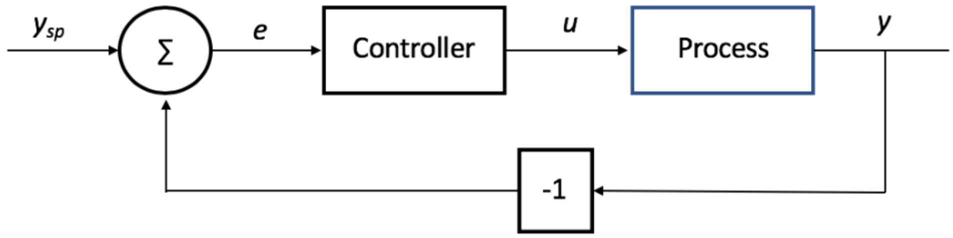

Fig. 1 - Feedback Process Loop

Where y_{sp} is the set point, e is the control error or $y_{sp} - y$, u is the signal from the controller to adjust the manipulated variable, and y is the output, or the process variable. The "textbook" version of the P.I.D. algorithm is described in equation 1 (Astrom 1995):

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right) \tag{1}$$

Where the control parameters are control gain K, integral time T_i, and derivative time T_d. Thus, the control variable is the sum of the proportional term, integral term, and derivative term.

On-Off control is the most basic form of this type of algorithm. As implied by the name, the system will activate the push the manipulated variable towards the set point and deactivate once the process variable reaches the set point. A good example of this is a simple thermostat. If the temperature is below the setting on the thermostat, the heater engages to increase the temperature. Once the temperature in the room reaches the setting, the heater deactivates. This method is simple, but oscillations about the set point are likely to occur as it is difficult to maintain steady-state.

Proportional control aims to avoid the oscillations present in on-off controllers. It does so by using the control error, e, and applying an action that is proportional to this error. Reducing Equation 1 for proportional control only:

$$\boldsymbol{u(t) = Ke(t)} \tag{2}$$

From this, we see that an error is necessary for proportional control to be active. For this reason, it is difficult to reach a steady-state using only proportional control, which necessitates the use for more terms in P.I.D. control. A low proportional gain would cause a slow build-up to the set point, while too large of a control gain would cause oscillations about the set point that decrease in magnitude over time.

The purpose of integral control is to eliminate the steady-state error that is associated with proportional only control. A small positive error will always lead to an increasing control signal and a small negative error will give a decreasing control signal. Larger values of T_i allow smoother control along the set point, but the response is much slower. Higher values give faster response, but with more oscillation.

Derivative control attempts to predict the future error by finding the derivative of the control error. Issues can arise with derivative control due to noise associated with the signal. It will not be discussed any further, as it is not applicable to the application being investigated.

Setting the integral or derivative time constants to zero eliminate that specific term from the control equation, and therefore, the controller. For example, setting T_d to zero means that the controller only relies on proportional and integral control, so it would be considered a P.I. controller. The most important constant is often considered to be the control gain, K, as it sets the overall aggressiveness of the controller (Badgwell et al. 2018).

1.3. Auto-driller Theory and Dysfunction

The history of automatic drilling control dates back over a century, but still require constant improvement and development. Increased sophistication of electronic control systems, mechanical braking, and signal processing contribute to advances in automatic control of drilling systems allowing for increased drilling efficiency and a more consistent steady state condition at the bit of specified parameters, presently being WOB, torque, delta p, or ROP (Florence, et al. 2009). Originally, auto-drillers on brake handle rigs employed pneumatic control systems to maintain constant string weight and were used to give drillers time to rest. Drillers could typically perform better manually than the controllers. (Boyadjief et al. 2003). Advancements in electronic computing technology allowed more efficient control of WOB in the brake handle systems, using proportional control.

Auto-drillers aim to control drum rotation speed. If in ROP mode, this speed is found by measuring the drum speed and converting it to ROP based on drum diameter, number of drum wraps, and number of lines strung (Pastusek, et al. 2016). Since these surface conditions used to find ROP do not change, ROP mode will give a smooth drum rotation speed. This is not always the case when using downhole conditions at the bit, such as WOB, torque, and delta P. When a mode other than ROP is active, the auto-driller must compare the present value of the specified parameter to the set point and command an ROP to the drawworks to maintain this value as close to the set point as possible. Typically, each parameter will have a set point, and the active parameter will be whichever is closest to its set point.

As formation strength changes, WOB would vary and therefore, torque and delta P. WOB and ROP are known to have a linear relationship while drilling without dysfunction. This relationship will change as rock strength varies, as a specific WOB would result in a slower ROP in a harder rock. This is shown in **Fig. 2**:

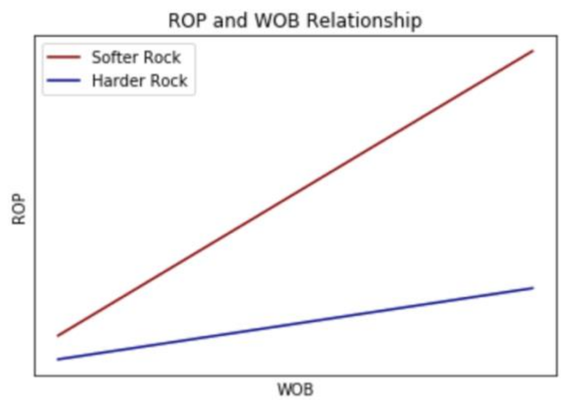

Fig. 2 - ROP and WOB Relationship for Differing Rock Strengths

Since this relationship is not always known, it is difficult for an auto-driller to have a specific ROP command for a given WOB. The controller will adjust the drum speed, measure the WOB response, and again adjust the drum speed. This process continues throughout the drilling process (Pastusek, et al. 2016).

The type of controller often used to convert the signal to a commanded ROP is a Proportional-Integral controller, or PI controller. Bang-bang, or on-off, controllers have been used but can result in WOB fluctuations due to the large deadband, which then leads to torque fluctuations at the bit, exciting torsional vibrations, commonly known as stick-slip. The PI controller aims to eliminate this deadband and provide steadier control of downhole conditions at the bit. The equation for a PI control loop in an auto-driller is shown is Equation 3:

$$\Delta ROP = \frac{WOB_{error}}{WOB_{range}} * P_{gain} * ROP_{range} + Integral\ Term \quad (3)$$

In this equation, the WOB_{error} is the difference in the WOB set point and the measured WOB across the range from 0 to set point, ROP_{range} is the range from 0 to the ROP_{max} entered, and P_{gain} is the proportional control gain to the WOB error. The integral term is used to adjust the integral error with respect to time to minimize the steady-state error (Pastusek, et al. 2016). From this equation, it is easy to see that if these values are not optimized or input correctly, the system can be unstable. Too high a P_{gain} or ROP_{range} can lead to instability as the drum speed would be increased too quickly, possibly causing an overshoot of WOB and torque at the bit. If these values are too small, the set point may never be reached. It is also important to make the connection between this equation, P_{gain}, and rock strength. As rock strength increased, ROP would be less for a given WOB. To maintain a smooth drum rotation rate, P_{gain} would have to be smaller for a harder rock strength. Once the bit transitions to a softer rock, P_{gain} would have to be increased or the system would take too long to reach its set point. The biggest concern with WOB oscillations is the oscillations of torque at the bit, which could excite stick-slip behavior and inefficient drilling.

A study by Occidental Oil & Gas Company in IADC/SPE-189653 highlights the importance of optimizing the control parameters by treating the range values and control gain values as if they are another a drilling parameter such as WOB or RPM. The gain values were step tested across multiple wells and the ROP setpoint (range) was raised to values 22-46% above the average realized ROP. Doing this reduced the error in the auto-driller and increased overall average ROP by 14.5% with the same WOB being applied. It was also noticed that gain settings do not display a clear relationship with the variability of instantaneous ROP. This confirms what is said in Patsusek's 2016 paper that gain should be adjusted when dysfunction is observed. The wells utilizing the roadmap also showed improvements in Mechanical Specific Energy (MSE) readings. MSE is a good tool to measure drilling efficiency. Technically, it is the energy required to break one volume of rock if drilling at 100% efficiency. Equation 4 was derived by Teale in 1965 to measure MSE while drilling (Teale 1965):

$$\boldsymbol{MSE} = \frac{\boldsymbol{Input\ Energy}}{\boldsymbol{Output\ ROP}} = \frac{\boldsymbol{480\ x\ TOR\ x\ RPM}}{\boldsymbol{Dia^2\ x\ ROP}} + \frac{\boldsymbol{4\ x\ WOB}}{\boldsymbol{Dia^2\ x\ \pi}} \tag{4}$$

The concept was proven by Pessier and popularized by Dupriest in the ExxonMobil Fast Drill Process (Pessier and Fear 1992, Dupriest and Koederitz 2005). It recognizes the linear relationship between WOB and ROP and between RPM and ROP. If MSE is increasing and it is not due to a lithology change, then dysfunction is also increasing. It is a valuable tool used to optimize drilling parameters by attempting to minimize MSE and avoid dysfunction. A lower MSE with optimized control gain values indicates an improvement in drilling efficiency by altering control gains when auto-driller dysfunction is noticed. There have even been lab-scale auto-drillers successfully implemented that focus on minimizing MSE rather than using a WOB or ROP set point. The objective is minimizing dysfunction and increasing drilling efficiency by altering WOB and RPM at specific times and observing MSE behavior. (Zarate-Losoya et al. 2018)

1.4. Stick-slip

Torsional drillstring vibrations, also known as stick-slip, can be excited due to instability in the auto-driller. During drilling operations, the drillstring can actually begin to wind up. This causes the bit speed to be less than the top drive speed and torque begins to build up in the drillstring. Eventually the torque builds up enough causing the bit to snap forward and spin ahead of the top drive. Small bit speed oscillations are typically not a major problem, but once this process gets severe enough the bit can actually come to a complete stop, also known as full-stick. Severe stick-slip can cause bit damage and slow drilling, so it is important to avoid this form of dysfunction if possible.

Stick-slip is recognized in real-time by oscillations in torque readings. One-second data can be sufficient enough to notice these oscillations, with the period typically being between 4-10 seconds (Dupriest, slide 3). As the length of the drillstring increases, the period will be longer due to less torsional stiffness in the string. This phenomena is very dependent on WOB. As WOB increases, depth-of-cut (DOC) will also increase, which then increases torque on the bit. This means that the string will twist up even more with higher WOB before snapping forward. An example of the torque oscillations used to identify stick-slip is shown in **Fig. 3**:

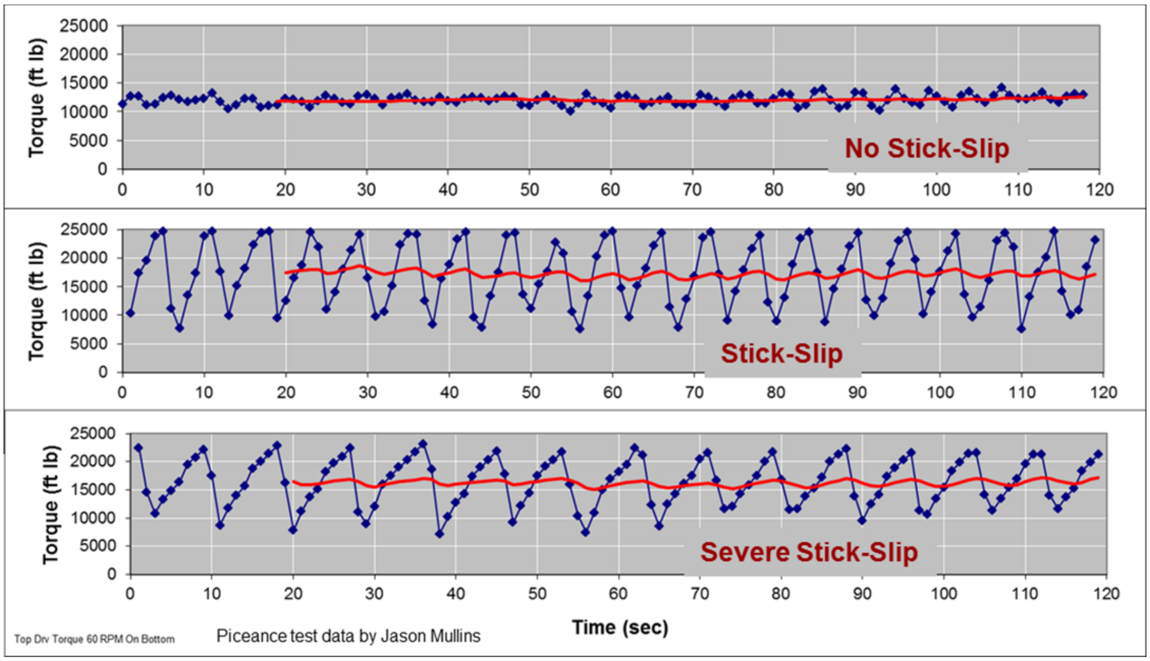

Fig. 3 – Stick-Slip Identification through Torque Cycles (Reprinted with permission from Pastusek, et al. "Drill Rig Control Systems: Debugging, Tuning, and Long Term Needs." SPE-181415-MS)

With Figure 3, it is easy to see to see that the significance of stick-slip depends on the magnitude of torque oscillations, and therefore bit speed oscillations. There will always be some degree of oscillations, but a small amount generally will not be detrimental to the drilling process or downhole tools. Full-stick can be seen in the lowest tracer of Figure 3. The asymmetric behavior of the torque readings means that the bit is coming to a full stop, building up torque, and then snapping forward ahead of the top drive.

Connecting this to control system dysfunction, oscillations in the commanded ROP can drive oscillations at the bit in WOB and therefore torque. Optimizing the control gain of the auto-driller will minimize any oscillations not due to formation changes or drillstring tension and compression, necessitating an algorithm that can automatically identify any instability in the drum rotation speed and adjusting the control gain accordingly.

1.5. DRCAT Algorithm

Control gains are typically controlled by the driller. The driller lower the gain if it appears that the system is unstable or raise the gain if it seems that it's taking too long to reach the set point. Drillers have a lot of responsibility on the rig. With safety and efficiency being of the highest priority, automating a task such as adjusting the control gain can allow drillers to focus their attention to other operations on the rig. SPE-191417-MS proposes a possible solution to this problem, the Drilling Rig Automatic Control Tuning (DRCAT) algorithm.

The algorithm monitors the commanded ROP, or ROP_{sp}, and adjusts the control gain once instability has identified. Two zones are established around a moving average value of ROP_{sp}, an inner zone and an outer zone. The widths of these zones are a specified multiple of the moving average standard deviation. The zones are established using Equations 4 through 10:

$$movavg_k = mu*ROPsp_k + (1 - mu)*movavg_{k-1} \quad (5)$$

$$movsmm_k = mu*(ROPsp_k)_2 + (1 - mu)*movsmm_{k-1} \quad (6)$$

$$movstd_k = \sqrt{\boldsymbol{movsmm_k - (movavg_k)^2}} \quad (7)$$

$$ozhilim_k = movavg_k + ozwfac*movstd_k \quad (8)$$

$$ozlolim_k = movavg_k – ozwfac*movstd_k \quad (9)$$

$$izhilim_k = movavg_k + izwfac*movstd_k \quad (10)$$

$$izlolim_k = movavg_k – izwfac*movstd_k \quad (11)$$

Where:

$movavg_k$ = moving average commanded ROP

$movsmm_k$ = moving average squared commanded ROP

$movstd_k$ = moving average standard deviation commanded ROP

$ROPsp_k$ = Commanded ROP

mu = moving average memory parameter

$ozhilim_k$ = outer zone high limit

$ozlolim_k$ = outer zone low limit

$ozwfac$ = outer zone width factor

$izhilim_k$ = inner zone high limit

$izlolim_k$ = inner zone low limit

$izwfac$ = inner zone width factor

There are 3 rules that govern the algorithm:

1. If the commanded ROP crosses the outer zone too quickly, rising above the outer zone upper limit ($ozhilim_k$) and below the lower limit ($ozlolim_k$) (or vice versa) within a specific time interval (*ozcdel*), decrease the WOB controller gain by a large factor (*ozgcf*).
2. If the commanded ROP crosses the inner zone too quickly, rising above the inner zone upper limit ($izhilim_k$) and below the lower limit ($izlolim_k$) (or vice versa) within a specific time interval (*izcdel*), decrease the WOB controller gain by a small factor (*izgcf*).
3. If the command ROP remains too long within the inner zone (between $izlolim_k$ and $izhilim_k$) for more than a specified time interval (*izolim*), increase WOB controller gain by a small factor (*izogif*).

Examples of how the control gain is adjusted using these rules are shown in simulated examples. **Fig. 4** shows how the control gain is decreased when instability is detected, with only the inner zone being shown:

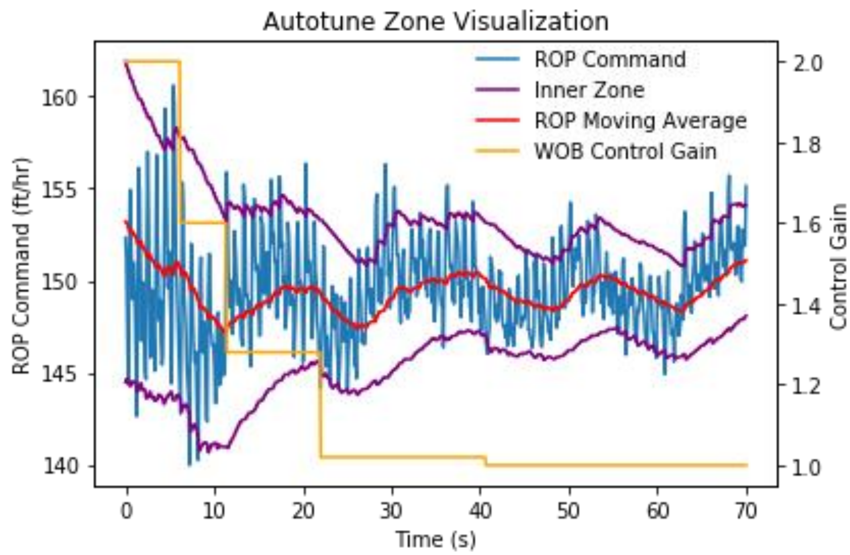

Fig. 4 - Decreasing Control Gain

Fig. 5 shows how the control gain would be increased, during a simulated transition to a lower rock strength:

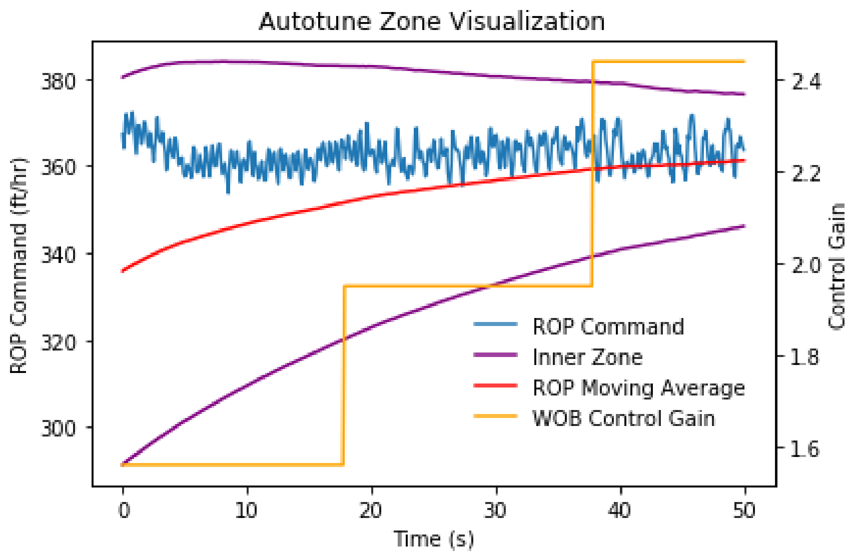

Fig. 5 - Increasing Control Gain

The objective of this study is to test this algorithm as a solution to automatically tuning the control gain to avoid auto-driller dysfunction. Complete optimization of inputs is not being considered at this time. Due to the limited testing time available for live rig data, zone widths will be determined using a simulator before live drilling tests commence.

2. TESTING

2.1. Simulator

Due to limited time availability and the logistics of testing the algorithm on a drilling rig during live drilling operations, a simulator was used to test the program. One limitation with the simulator that should be noted is that it does not contain a spring constant for the drillstring, so tension and compression is not considered. There were two major objectives when testing on the simulator: First, to test if the algorithm improves the stability of commanded ROP. Second, to optimize the inputs as best as possible before live testing. The first objective was easily confirmed. Simulating a transition to a harder rock showed a significant improvement and is displayed in **Fig. 6**:

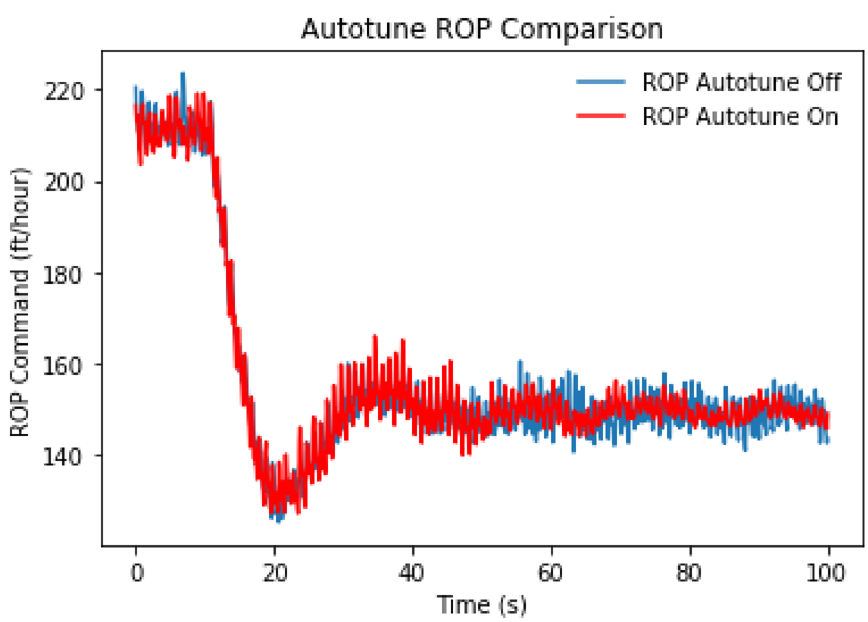

Fig. 6 - Commanded ROP with Autotune Off and On

Fig. 6 shows a noticeable improvement in the stability of commanded ROP, and therefore, a steadier rotation speed. **Fig. 7** shows the same simulations during the 70 second window shown in Figure 4:

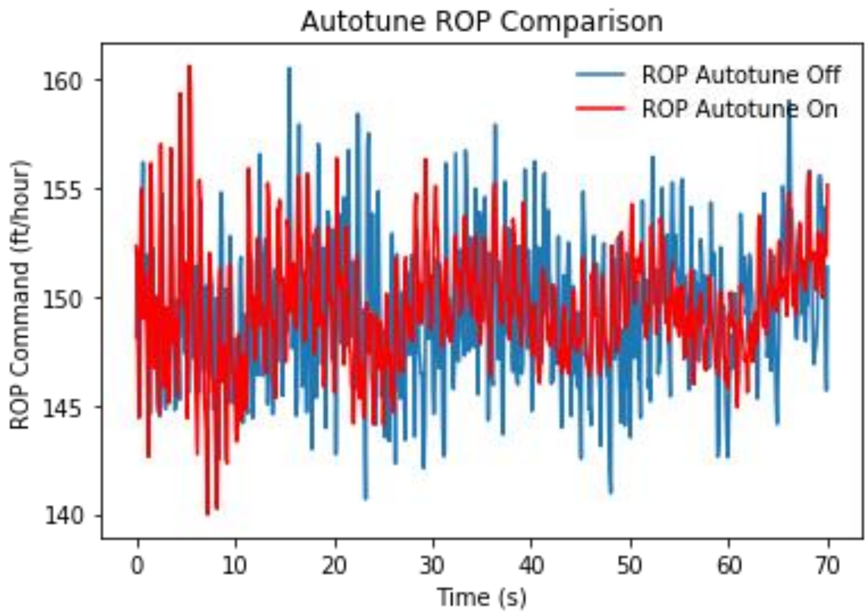

Fig. 7 – Post-Transition ROP Stability Comparison

Standard deviation of ROP during the window shown in **Fig.7** is 3.25 with the autotune off and 2.71 with the autotune on. Ultimately, a steady WOB is desired, so the simulated WOB was also compared for the same simulations. **Fig. 8** shows WOB comparison for the same rock strength transition, while **Fig. 9** shows the 70 second window from **Fig. 4** and **7**:

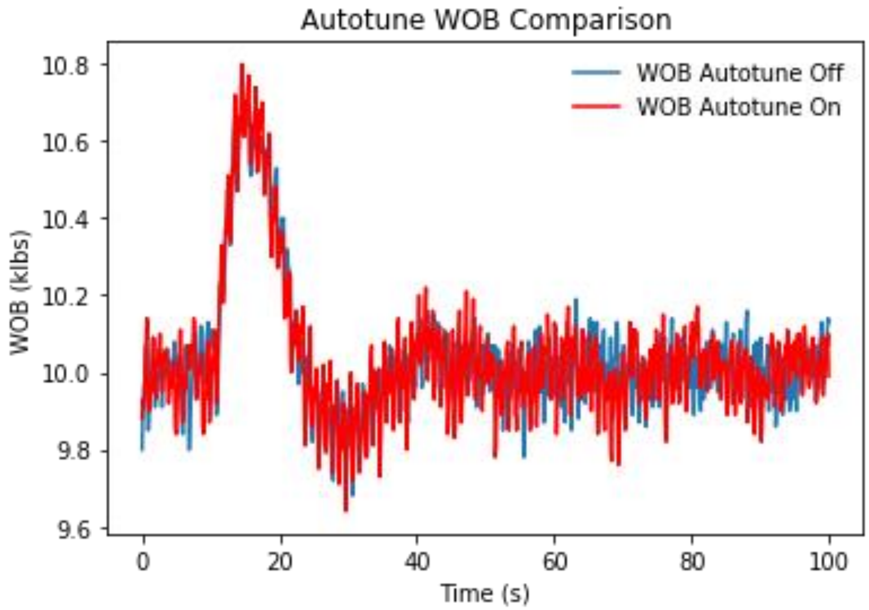

Fig. 8 - WOB with Autotune On and Off

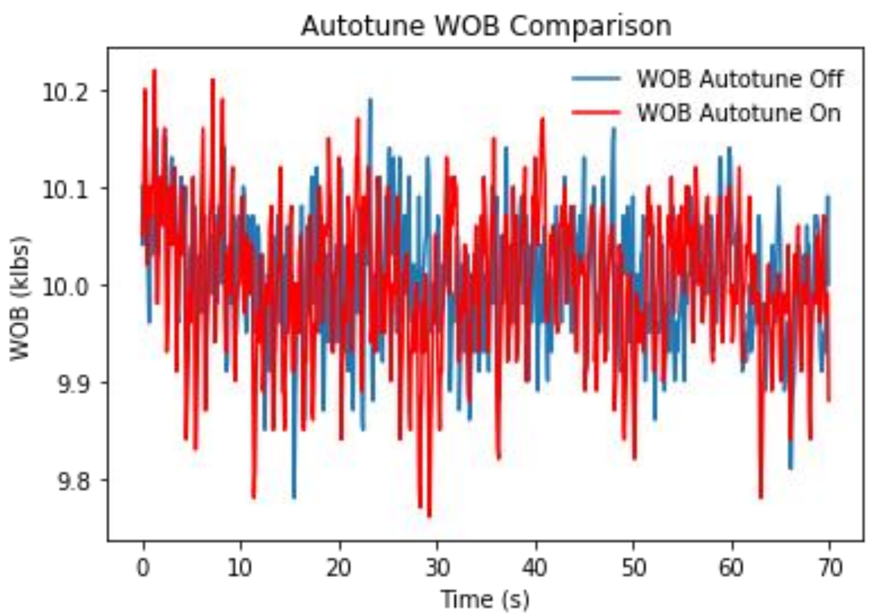

Fig. 9 - Post-Transition WOB Stability Comparison

The standard deviation of WOB in **Fig. 9** is 0.062 with autotune off and 0.075 with autotune on. Interestingly, this is a very small difference with the autotune off actually showing slightly better stability. This could be due to errors in the simulator program or the change in simulated rock strength not being significant enough, but the improvement in commanded ROP was enough to justify live testing of the algorithm.

The second objective of simulator testing was to optimize the values, specifically widths of the zones and the mu value to avoid false triggering from noise in the signal. The original values from the authors of the algorithm are *ozwfc* = 2 and *izwfc* = 1. It was noticed on the simulator that these values are too small, as noise was causing false triggers. Even if commanded ROP is stable, an increase in control gain would never happen due to constant triggering. These inputs were compared with varying mu values as well. The mu input is described as a memory parameter by the authors. It is essentially a filter that weights historical values of ROP more if small values of mu are used. Regardless of the mu value, there was significant false triggering due to noise. After much testing, it was decided that the values used going forward would be *ozwfc* = 2.5, *izwfc* = 2, and *mu* = 0.05. Using these inputs, it was noticed that the outer zone is only triggered in extreme instances, but it was determined this would not be a problem.

2.2. Live Testing

Live testing was conducted on a Patterson-UTI rig in the Eagle Ford formation. The testing was conducted over two rig trips, allowing testing on surface drilling and lateral drilling. The data available came from the auto-driller, meaning that RPM and depth data were not available. The control gain values were limited to 4.0 as a maximum and 1.0 as a minimum.

2.2.1. Surface Drilling

The first test was conducted while drilling surface. For the program to be active, the auto-driller must be in WOB mode. While drilling surface, low WOB is used to achieve the desired ROP, so an ROP set point was typically used and the auto-driller was run in ROP mode. When WOB mode would be active, it would be for very brief amounts of time. The algorithm requires time to decrease the control gain, reach stability, and then begin increasing the control gain. WOB mode being active for only seconds at time. **Fig. 10** shows a 45 second window where WOB was mostly active and the algorithm adjusted the control gain. The instances where there are gaps in the ROP data are short time periods where the auto-driller reverted back to ROP mode. The control gain is decreased from 2.56 to the minimum of 1.0. The gain would then stay at 1.0 and not increase due to the controller switching back to ROP and not having time to reach stability, and the control gain had to be manually reset. With such limited data it wasn’t possible to draw a firm conclusion on the algorithm, but it was apparent that it was not effective in surface drilling when ROP mode was prevalent.

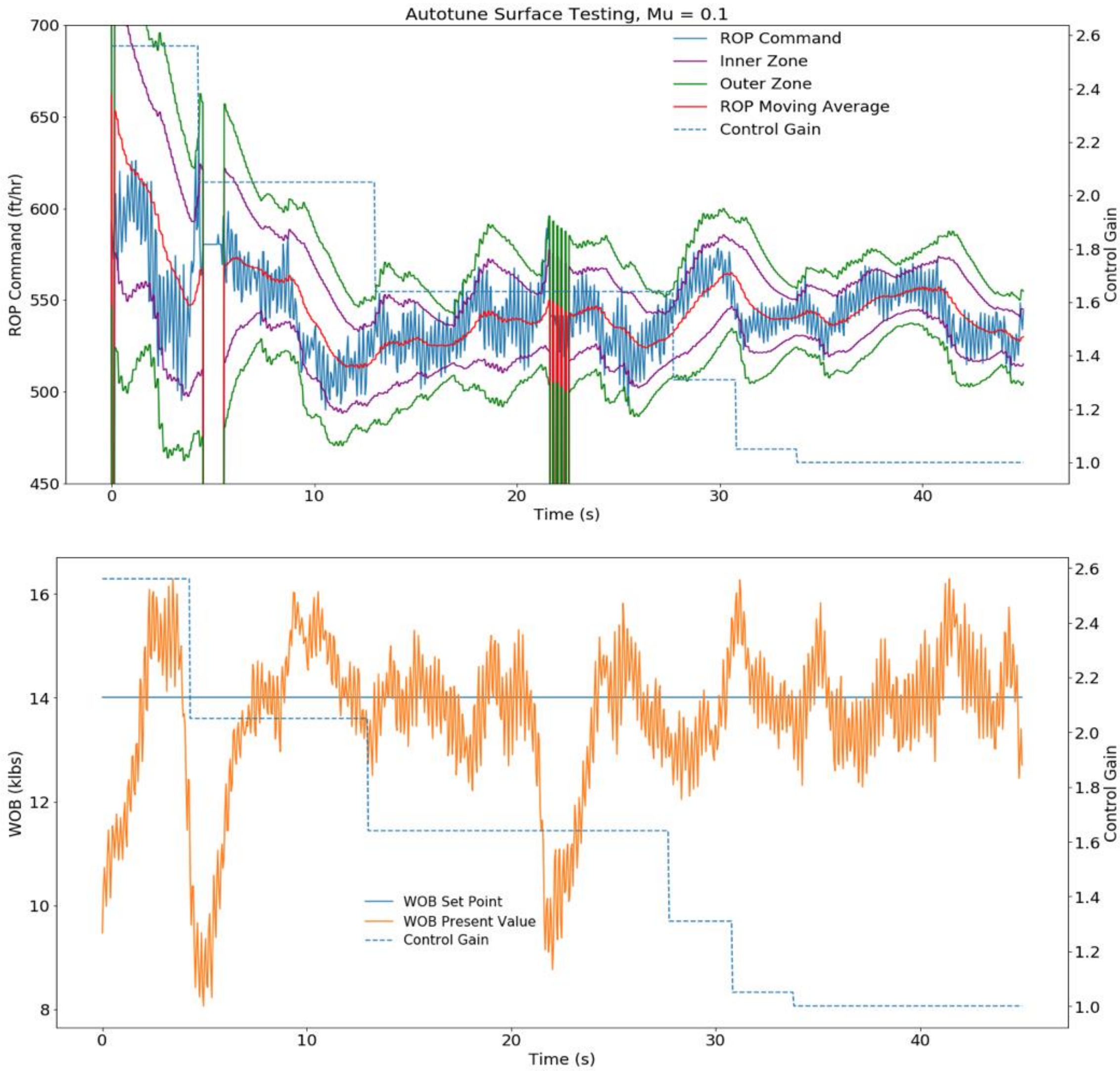

Fig. 10 - Surface Drilling ROP and WOB

2.2.2. Lateral Drilling

The next opportunity for testing during drilling operations was while drilling the lateral of the well. While monitoring data in real time, the program was active much longer and changes in control gain in both directions were occurring. The program was limited to rotation. Concerns about adjusting the control gain during sliding were noted so it was decided that a constant gain would be used during that time and the focus would be on rotation. Once the data was visualized, it was obvious that a much better study could be conducted than while drilling surface. The program was active for complete stands of drill pipe, with the control gain being adjusted in both directions for minutes at a time.

The study aims to determine if the algorithm helps the system reach stability more quickly than if the control gain were constant. To achieve to this goal, situations when instability is noticed will be compared while control gain is constant vs when the program is actively adjusting it. **Fig. 11** shows a situation with an unstable commanded ROP but a constant control gain. ROP Setpoint has also been plotted, as it is a factor in the WOB controller.

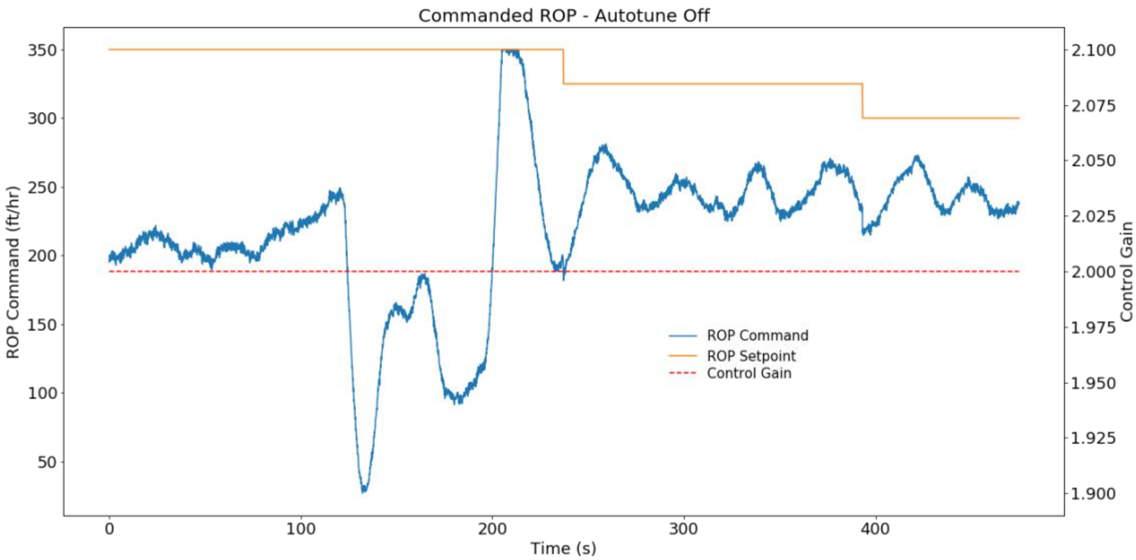

Fig. 11 - Unstable ROP Command with Autotune Off

Instability is noticed early in this time frame, with an ROP oscillation of over 300 ft/hr. Since we're ultimately concerned with WOB and torque at the bit, we'll next need to look at these. **Fig. 12** shows WOB during this same time frame.

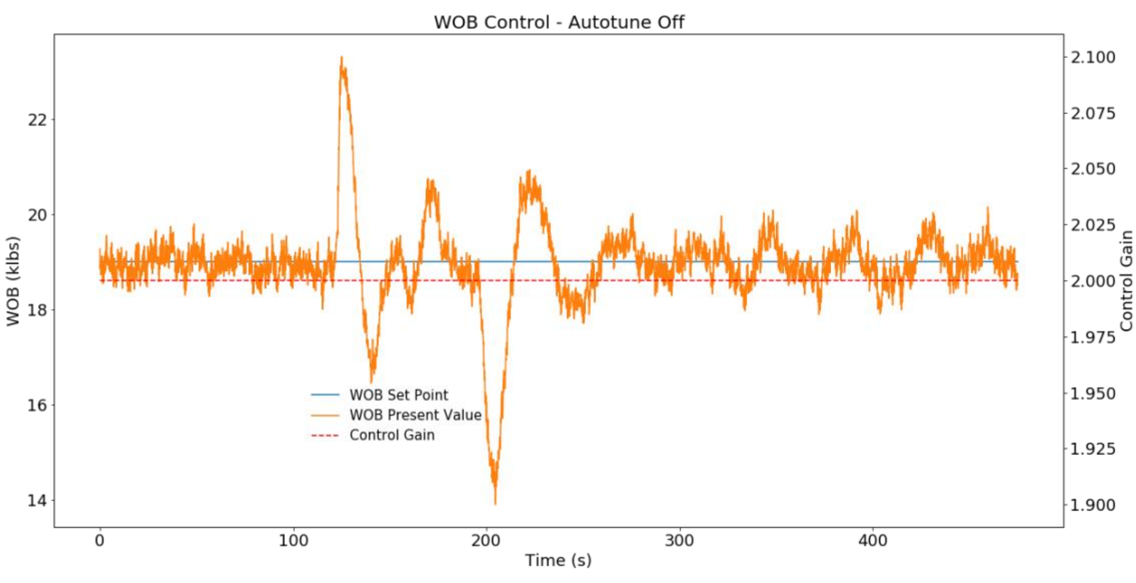

Fig. 12 - Unstable WOB with Autotune Off

This is the typical response expected during this situation, an unstable WOB reading followed by an overshoot of the set point before the system eventually reaches stability. The DRCAT algorithm would have been triggered, reducing the control gain. Using P.I.D. theory, it would have avoided or lessened the overshoot, but weight would have been brought back to the set point more slowly if the low gain were constant. The algorithm takes this into account though and begins increasing the control gain to avoid this slow build up. In the three instances of dysfunction noticed in the data with the constant control gain, some degree of overshoot was noticed. **Fig. 13** displays these three instances.

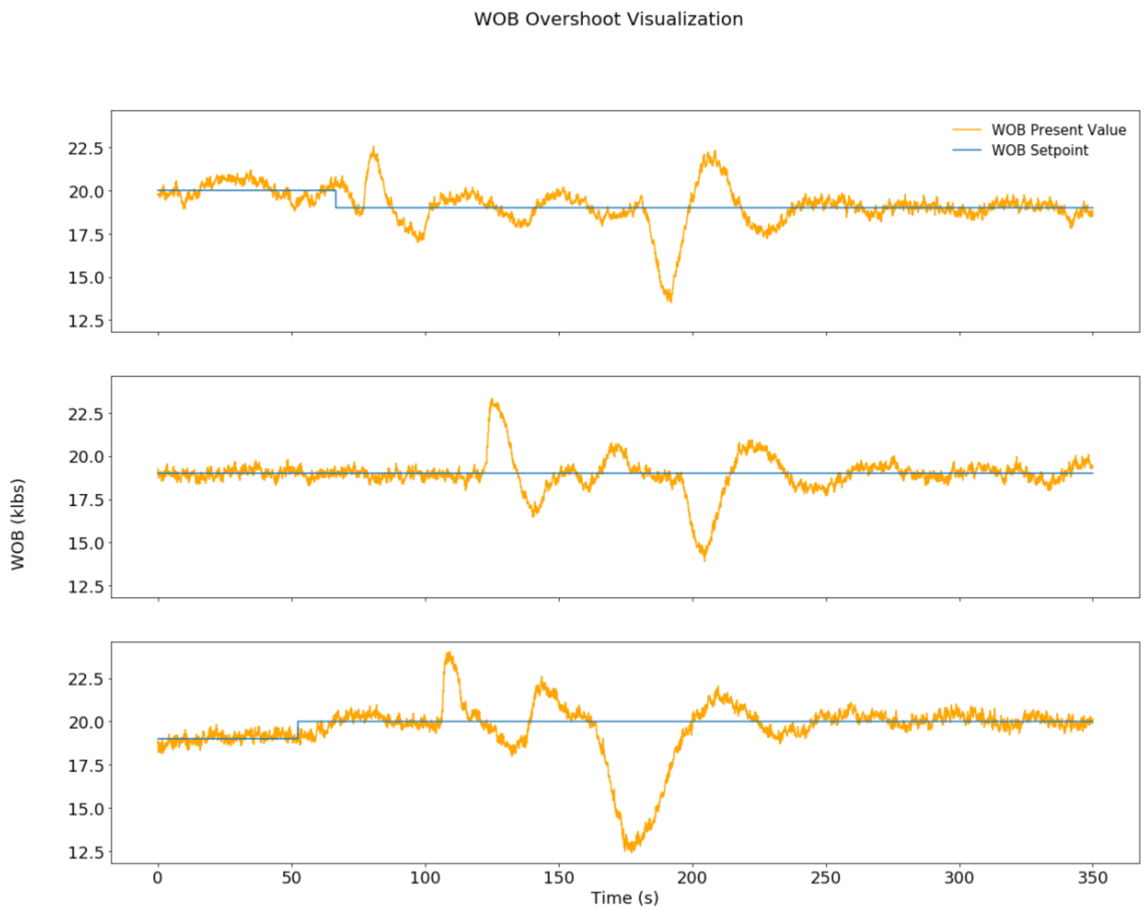

Fig. 13 - WOB Overshoots with Autotune Off

The next step was to study the data collected to see if any scenarios similar to the previously described existed and how the algorithm handled it. **Table 1** summarizes the program inputs for the first test.

Table 1 - DRCAT algorithm inputs for live testing

mu	0.05	moving average memory parameter
ozwfc	2.5	outer zone width factor
ozcdel	10	outer zone cross delta time (s)
izwfac	2	inner zone width factor
izcdel	10	inner zone cross delta time (s)
izolm	10	inner zone occupancy limit (s)
ozcgf	0.5	outer zone cross gain cut factor
izcgcf	0.8	inner zone cross gain cut factor
izogif	1.25	inner zone occupancy gain increase factor

Many of these are the same as the algorithm authors used in original simulator testing in SPE-191417-MS. The width factors were optimized during simulator testing. **Fig. 14** shows the control gain being adjusted, along with commanded ROP, moving average standard deviation, and the inner and outer zones.

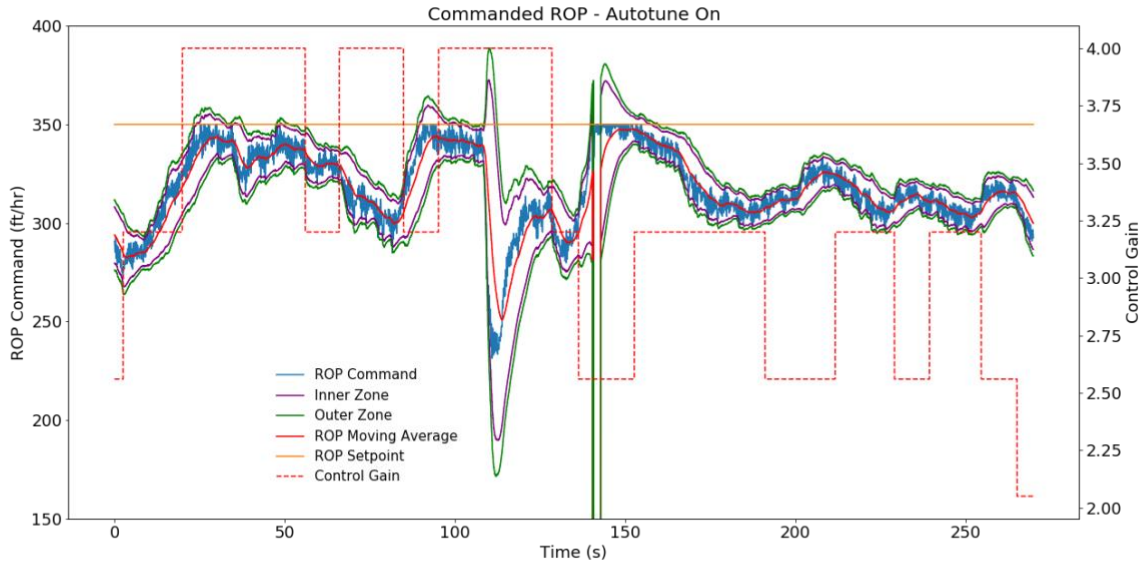

Fig. 14 - Commanded ROP with Autotune On

The algorithm detects the instability and starts to decrease the control gain. Note that WOB mode does deactivate for a brief period of time but reactivates not long after. It is difficult to determine the impact the control gain has using this data, so WOB is also displayed in **Fig. 15**:

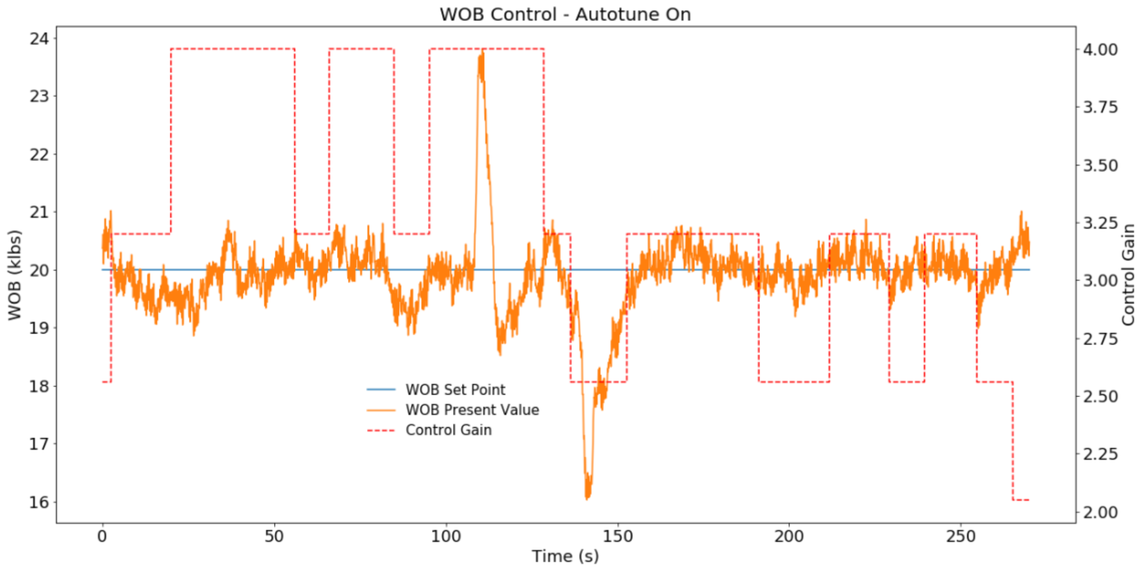

Fig. 15 - WOB Control with Autotune On

The increasing control gain at around the 150 second mark shows the program correctly recognized that the WOB was being brought up to set point and an increase would bring it up more rapidly. The overshoot shown in **Fig. 13** is also much less significant. Interestingly, the control gain is still greater in the scenario in **Fig. 15** vs that in **Fig. 13**. Once the set point is reached, there is constant adjustment of the control gain. This could be deemed unnecessary if the system is close to stable.

Fig. 16 shows another scenario where dysfunction occurs and the control gain is adjusted.

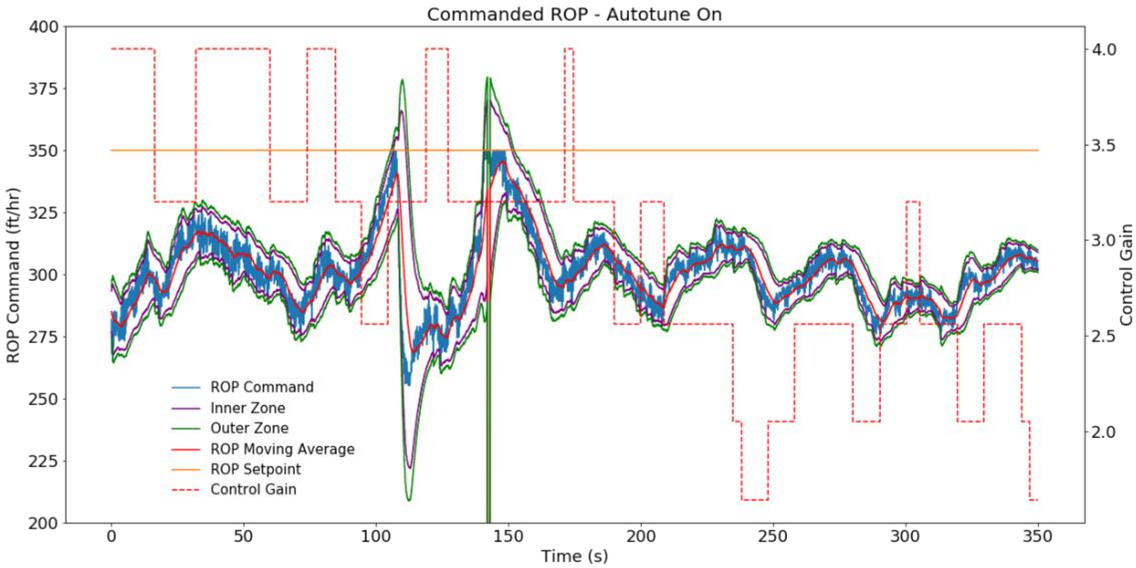

Fig. 16 - Commanded ROP with Autotune On

And the corresponding WOB:

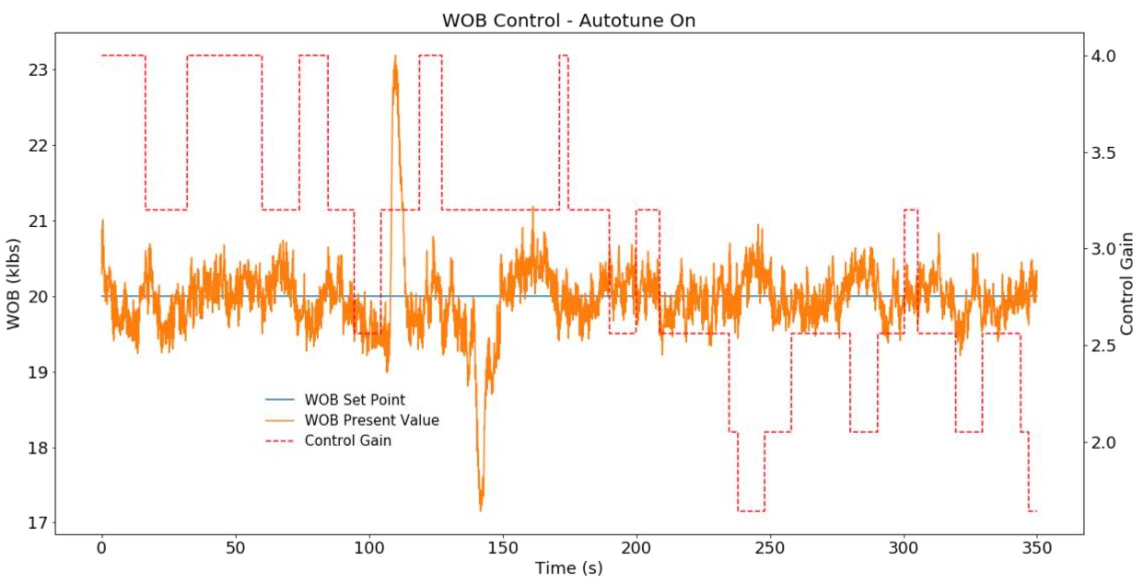

Fig. 17 - WOB Control with Autotune On

There is a slight overshoot in WOB noticed in **Fig. 17**, followed by continuous adjustments of control gain. Looking at these repeated adjustments, it might be unnecessary. There is always some error present and increasing the gain could theoretically move it further from the setpoint. The *izolim* was doubled from 10 seconds to 20 seconds, which would make the control gains lower due to the doubled time window before the gain increased. **Fig. 18** and **19** show commanded and ROP and WOB with the longer window.

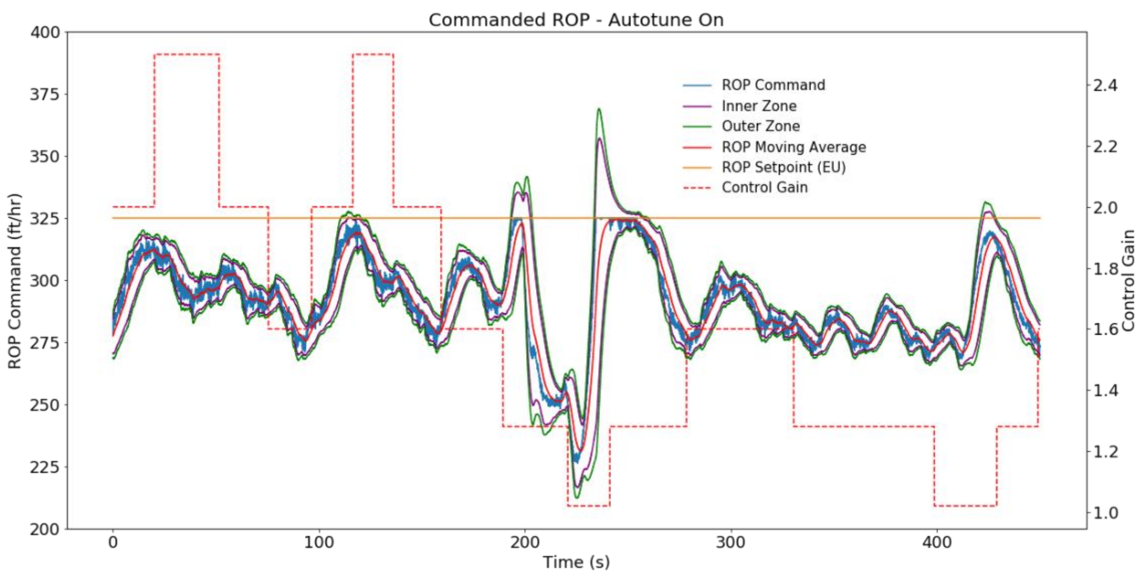

Fig. 18 - Commanded ROP with Autotune On and izolim Extended

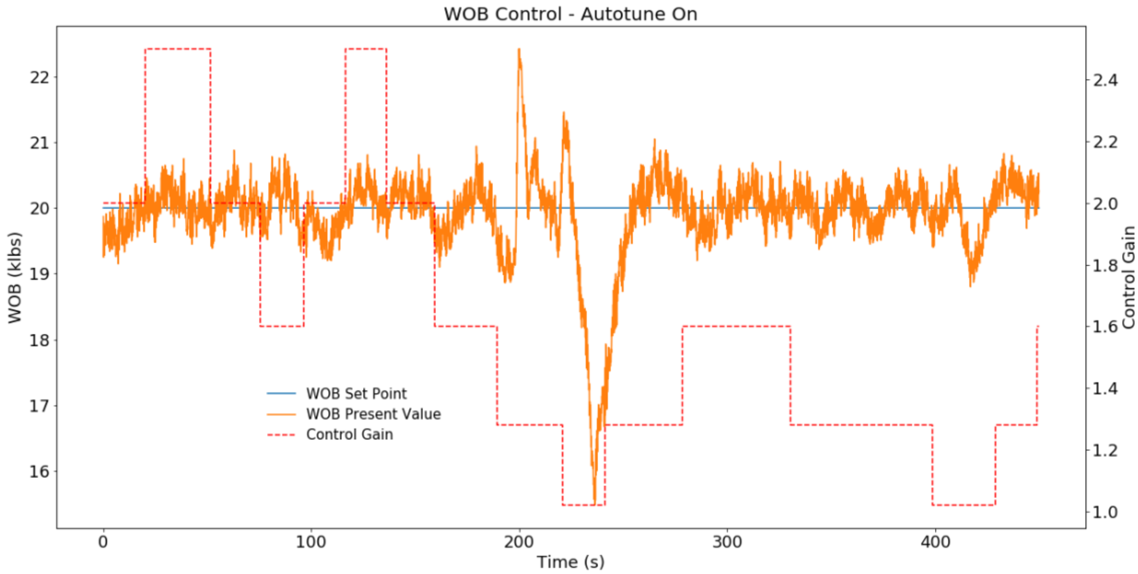

Fig. 19 - WOB with Autotune On and izolim Extended

Very similar behavior to the other instances with autotune enabled. Commanded ROP appears to be slightly more stable after the decrease in control gain. **Table 2** summarizes the standard deviations of WOB with autotune on and off during three different instances of stability.

Table 2 - WOB Standard Deviation

Autotune On	**Autotune Off**
0.32	0.29
0.32	0.36
0.32	0.305

The standard deviation of WOB with autotune on is pretty consistent when at or near setpoint. It's slightly more variable with autotune off but there isn't sufficient evidence to say that control is improved with the autotune on. Next would be to investigate differential pressure, as it's a better indicator of weight transfer to the bit when drilling deviated.

There exist problems in using the differential pressure controller for the auto-driller. The delay in the signal using mud-pulse telemetry can cause control issues as the downhole environment can rapidly change by the time the controller reacts to the signal. There is also literature providing evidence that differential pressure control can induce stick-slip at the bit (Adam 2018). This makes it worth comparing differential pressure data while in WOB mode in the lateral.

Fig. 20 shows WOB and differential pressure over the length of the stand.

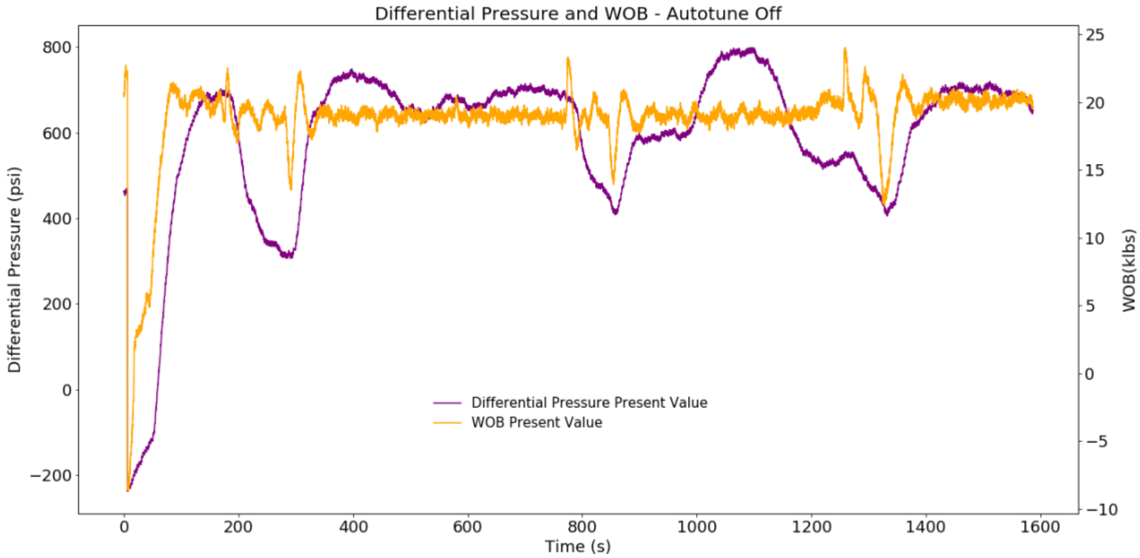

Fig. 20 - Differential Pressure and WOB Comparison with Autotune Off

It's easy to see the delay in the differential pressure signal while ramping up WOB. It's also interesting to see that differential pressure is not always directly correlated to the WOB reading. For instance, just before 200 seconds there is a small spike of about 1,000 lbs. in WOB, but no significant increase in differential pressure, but there is a major decrease not long after. In fact, in the three noticeable sections of dysfunction, similar behavior is seen. What is apparent is that the actual WOB reading is not necessarily what the bit is actually experiencing.

Fig. 21 displays the differential pressure and WOB in the section that the autotune was engaged.

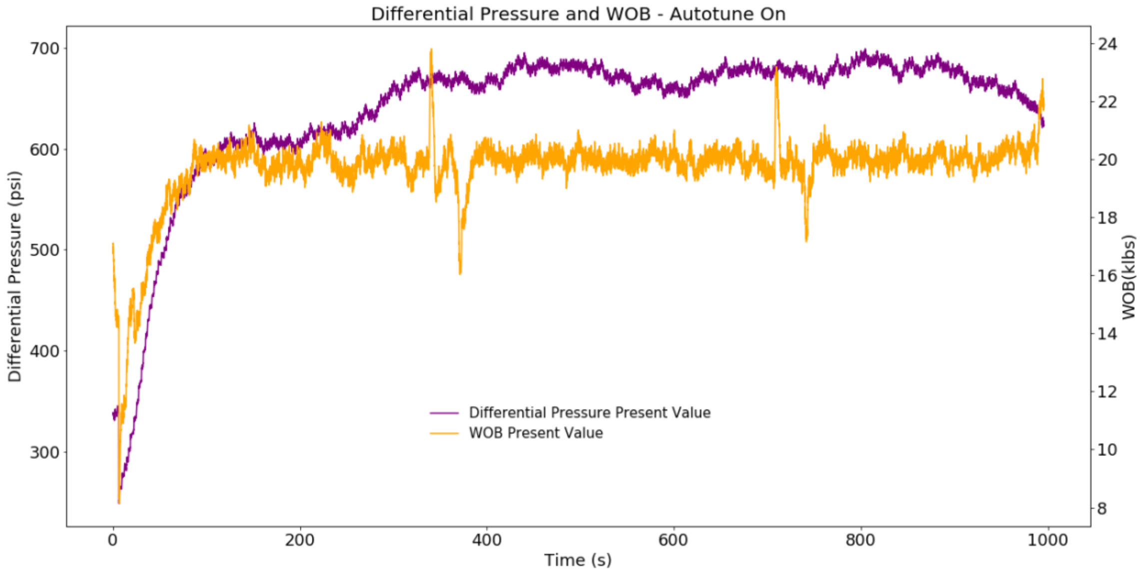

Fig. 21 - Differential Pressure and WOB Comparison with Autotune On

Upon first inspection, it looks like a much better result with much smoother control, but such a major difference does not seem practical. What is important to note and one of the key reasons that differential pressure is being investigated, is that the high WOB reading that triggered the dysfunction was not due to the drillstring slipping after breaking friction from the bottom of the borehole. That being said, it is interesting to see the behavior of the control gain over the course of the full data set, as shown in **Fig. 22**:

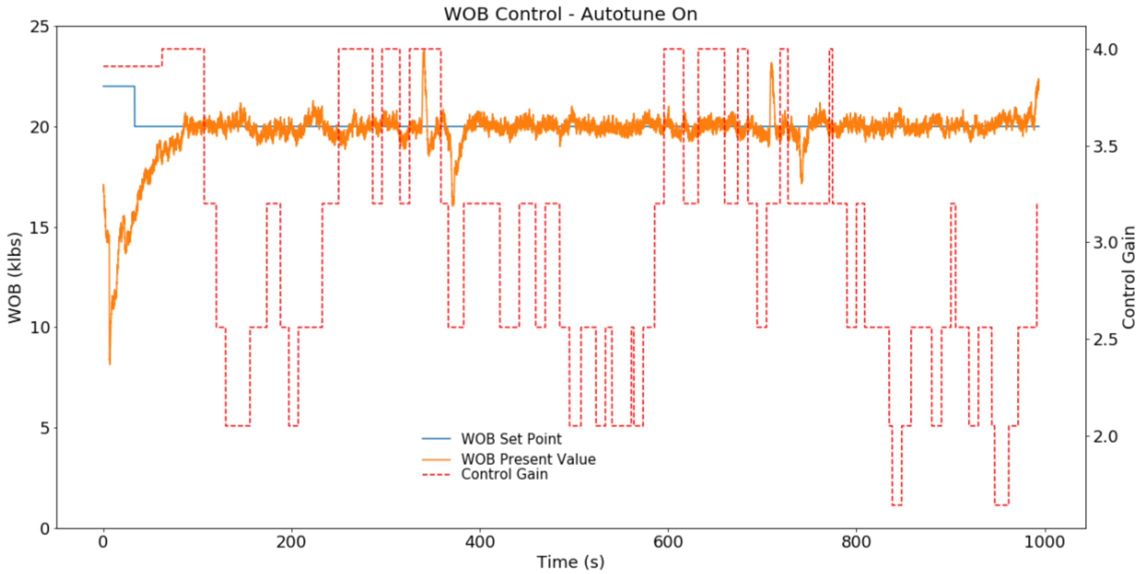

Fig. 22 - WOB - Autotune On

The program is constantly adjusting the control gain as desired and it might seem as though it's making a difference when looking at differential pressure, standard deviation of WOB, and the time for WOB to become stable again, but the control gain is still often higher than in the case with autotune off, which theoretically should not be the case. A higher gain would help WOB reach setpoint quickly, but would reach steady-state as quickly as a smaller control gain. The data set is small and more study would be required before the algorithm can be either a confirmed solution, but with the data presented it does not appear to be a solution to the problem in shallow, surface drilling and more investigation would be necessary in other sections. It may improve stability in the lateral, but weight transfer in this section is not always directly to the bit bringing into question the importance of the problem. WOB reading does not directly correlate to differential pressure. If control of weight at the bit is what is desired, then improved ways of differential pressure control should be investigated.

3. CONCLUSION

3.1. Conclusion

The DRCAT algorithm has been investigated as a possible solution to auto-driller dysfunction. Theoretically, the algorithm does as it's designed. It decreases control gain when unstable to help reach steady-state and increases control gain when ramping up to the setpoint. This behavior is shown in both simulator and live drilling when the WOB controller is active for extended periods of time. In a simulator setting, commanded ROP is vastly improved. In surface drilling, the algorithm is not a viable solution to auto-driller dysfunction due its time dependence in order to increase the control gain. Manual mode had to be used. In lateral drilling, the algorithm behaves properly but results are mixed. There isn't enough data to say WOB control is improved with constant adjustment of control gain. WOB overshoots are less prevalent with the autotune on in the data. The control gain is adjusted accordingly, decreasing when unstable and increasing when stable or increasing WOB, but if WOB is near setpoint this might be unnecessary. Given this behavior though, it could prevent an auto-driller from becoming extremely unstable, leading to extreme oscillations.

Future work should start with testing on an intermediate testing. It would be interesting to see the effects the algorithm has with more pronounced lithology changes and with WOB mode active. If RPM data is available, it would also be interesting to see if any improvements of drilling efficiency are present. This could be done through MSE and depth-of-cut monitoring and comparison with offset wells. Sensitivity analysis on the inputs could also be of consideration.

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