Nonlinear Model Predictive Control of Managed Pressure Drilling Based on Hammerstein-Wiener piecewise linear models

2015 Fall AIChE Meeting

by Junho Park

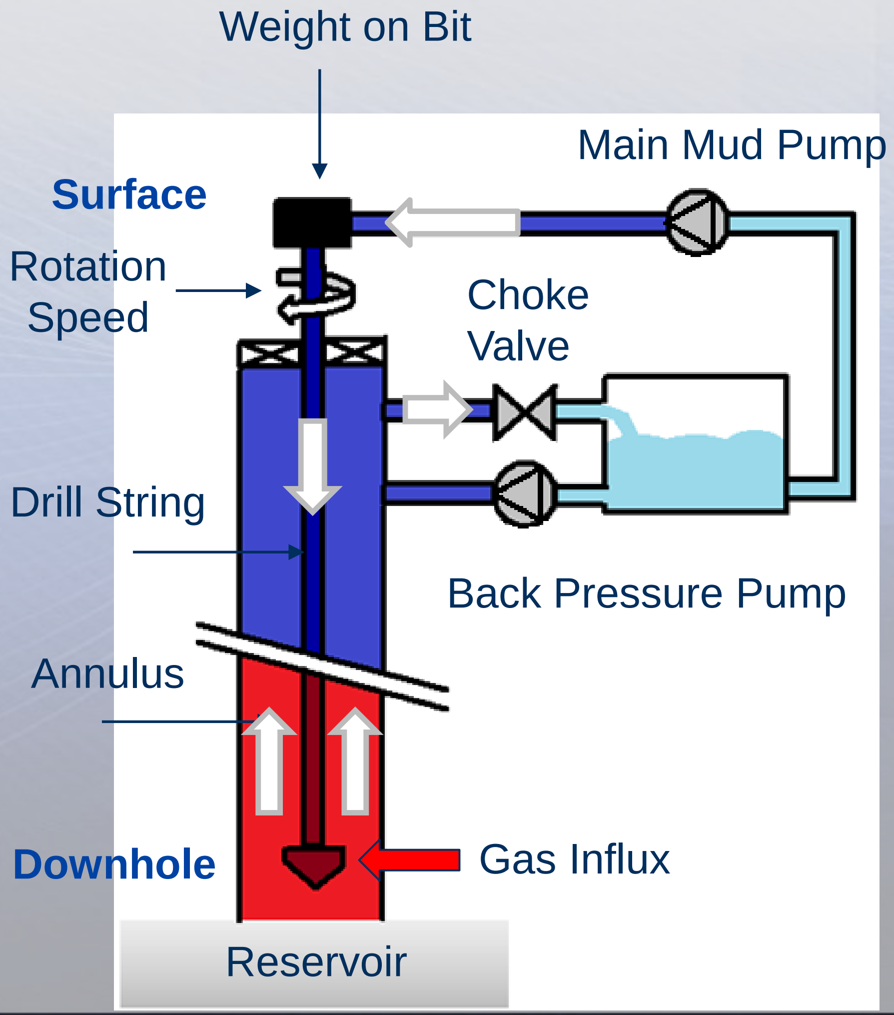
Outline

- Overview the Managed Pressure Drilling Process

  - Motivation and Challenges

- Downhole Pressure Control using Lower Order Model
- Downhole Pressure Control using Hammerstein-Wiener Model
- Conclusion and future work

Managed Pressure Drilling



Measurable variables:
- Surface measurements
- Downhole pressure (mud pulse / wired pipe)

Unmeasurable variables in annulus:
- Downhole pressure (non wired pipe)

Why Automate MPD?

- Average of 4 uncontrolled well situations in the Gulf of Mexico each year (Morris, 2014)
- MPD Automation Project objectives:
  - Regulate downhole pressure with a controller that changes chokes and pumps
  - Combine pressure control with ROP maximization with a controller that changes chokes, pumps, RPM, and WOB
  - Identify and attenuate unexpected gas influx
  - Detect and automate cleaning of cuttings buildup

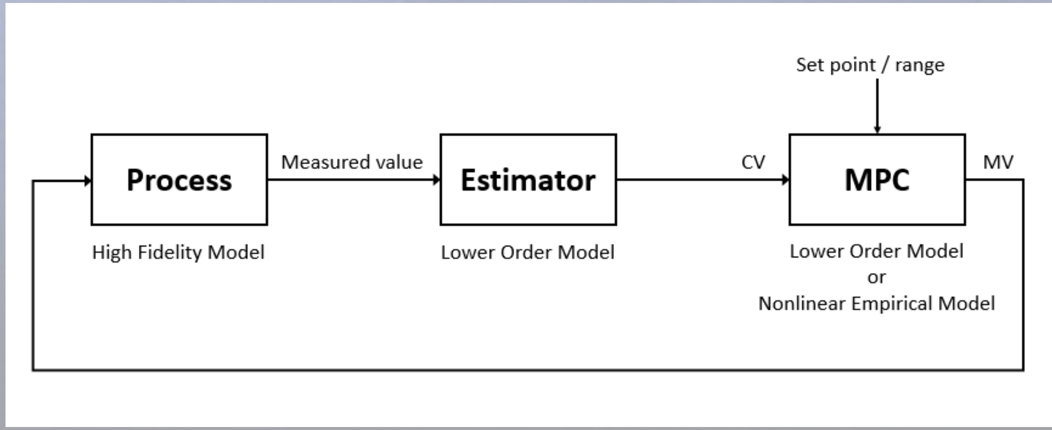
Deepwater Horizon 2010

[1] Morris, D., Analysis of Well Control Incidents 2007-2013, U.S. Dept. of the Interior, Presented by Dan Fraser at the 2014 SPE ATCE Meeting, Amsterdam, The Netherlands

Types of Models for MPC

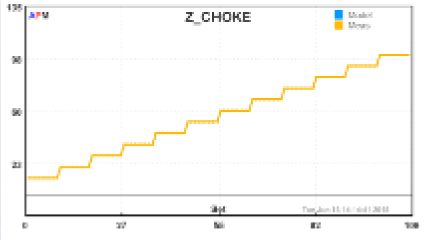
First Principles Model - High Fidelity Model (WeMod, SINTEF, OLGA)
- Lower Order Model (Stames et al.)

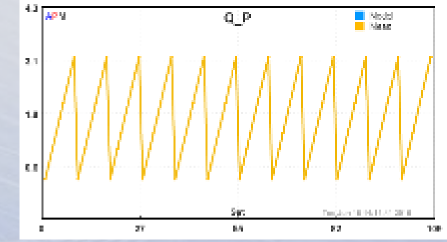
Empirical Model - Linear Empirical Model
(e.g. Transfer function, State-space, ARX, OE etc)
- Nonlinear Empirical Model
(e.g. Nonlinear ARX, Hammerstein-Wiener Model etc)



Fitting data with Steady State Values

Estimate the initial parameters in Lower Order Model





$$\dot{p}_p = \frac{\beta_d}{V_d}(q_{pump} - q_{bit})$$

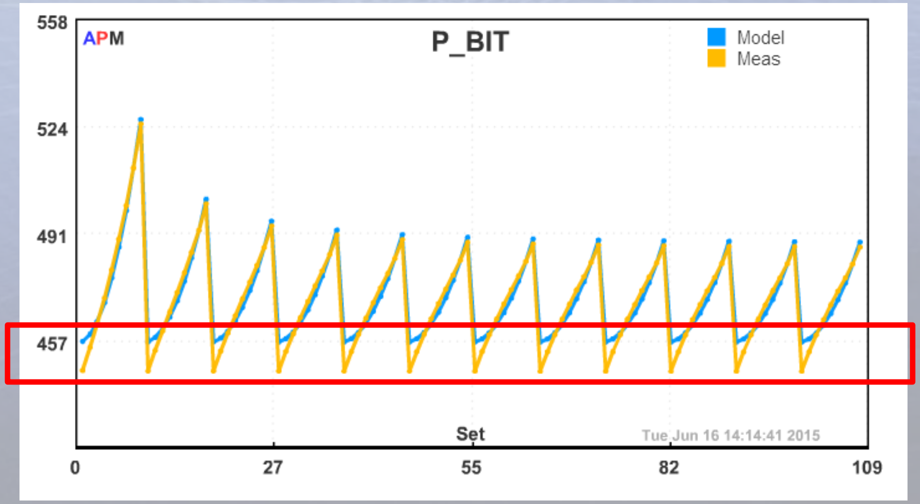
$$\dot{p}_c = \frac{\beta_a}{V_a}(q_{bit} + q_{back} - q_{choke} + q_{res} - ROP \times A_a)$$

$$\dot{q}_{bit} = \frac{1}{M}(p_p - F_d|q_{bit}|q_{bit} + \rho_d g h_{bit} - p_{bit})$$

$$\dot{h} = ROP$$

$$p_{bit} = p_c + \rho_a F_a |q_{bit} + q_{res}|(q_{bit} + q_{res})h + \rho_a g h_{bit}$$

$$p_i - p_{i+1} = \rho_{a,i} F_{a,i} |q_{bit} + q_{res}|(q_{bit} + q_{res})(h_i - h_{i-1}) + \rho_{a,i} g(h_{v,i} - h_{v,i-1})$$

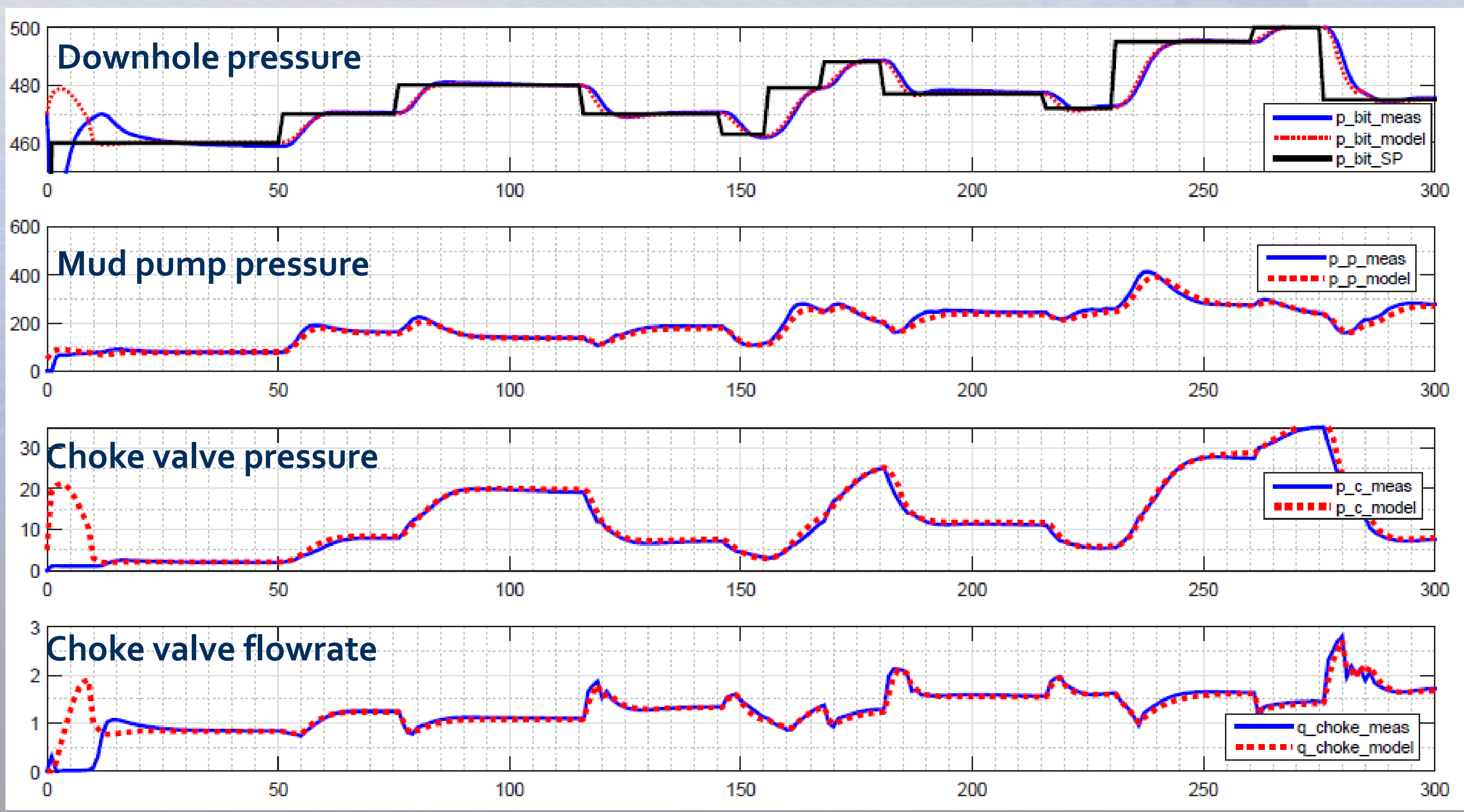


Not a good agreement at low pressure range

It results a model mismatch when pipe connection takes place

For Non-wired drillpipe rigs

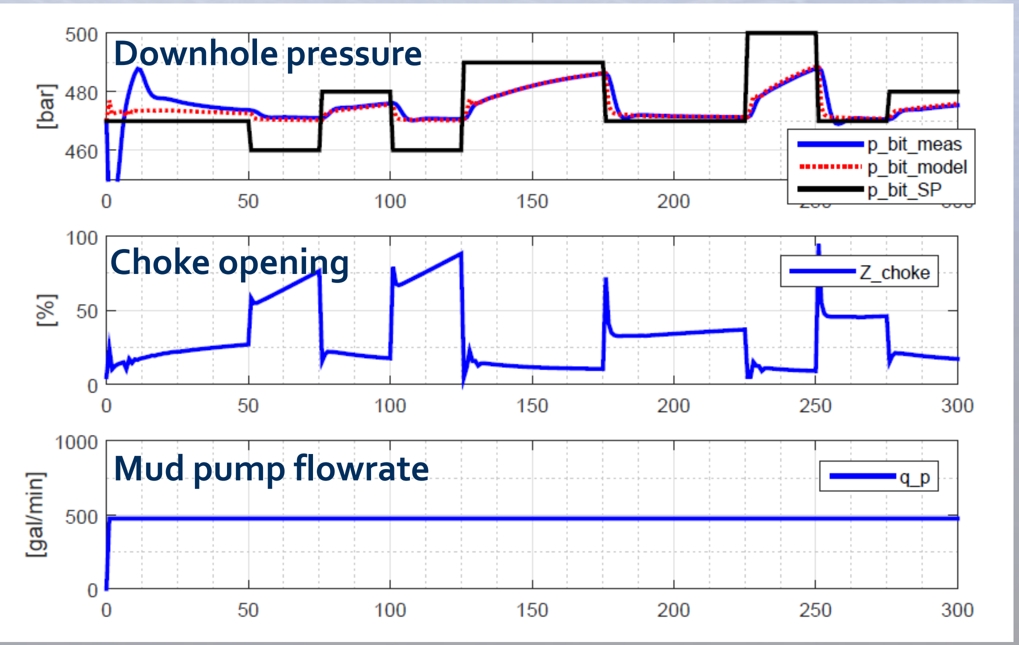
- Estimate the downhole pressure using surface measurements via MHE
- MHE employs the Lower Order Model



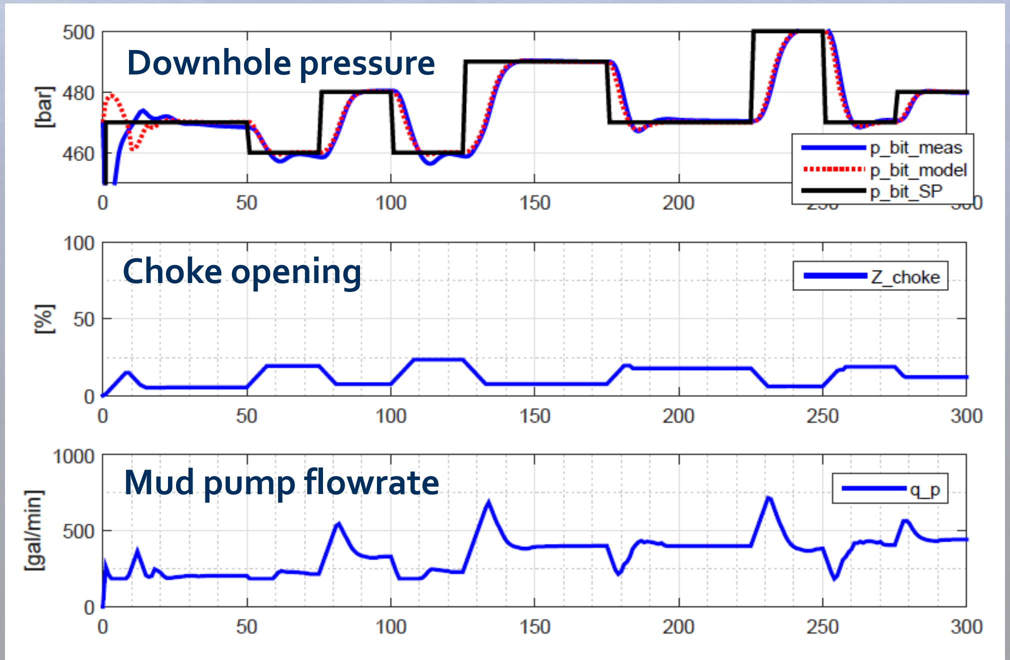
PID and Model Predictive Control

Performance comparison for Downhole pressure control

Conventional (PID)

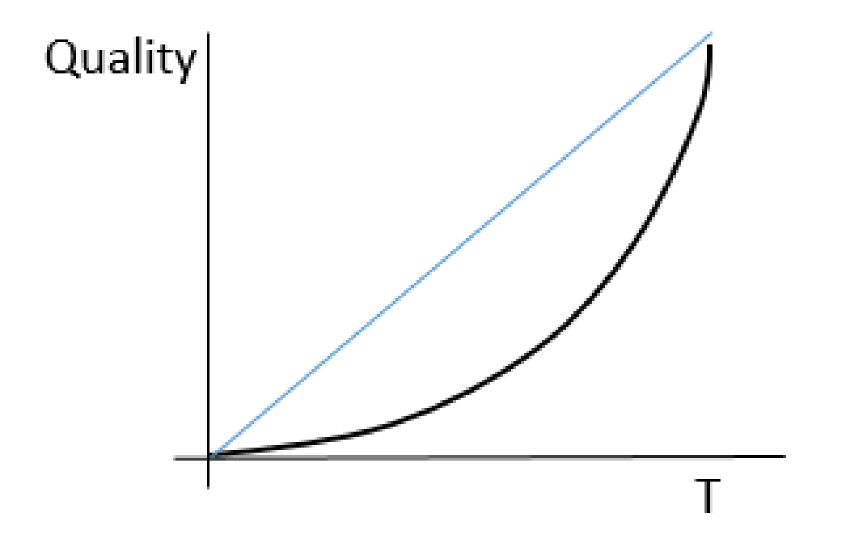


Advanced (MPC)

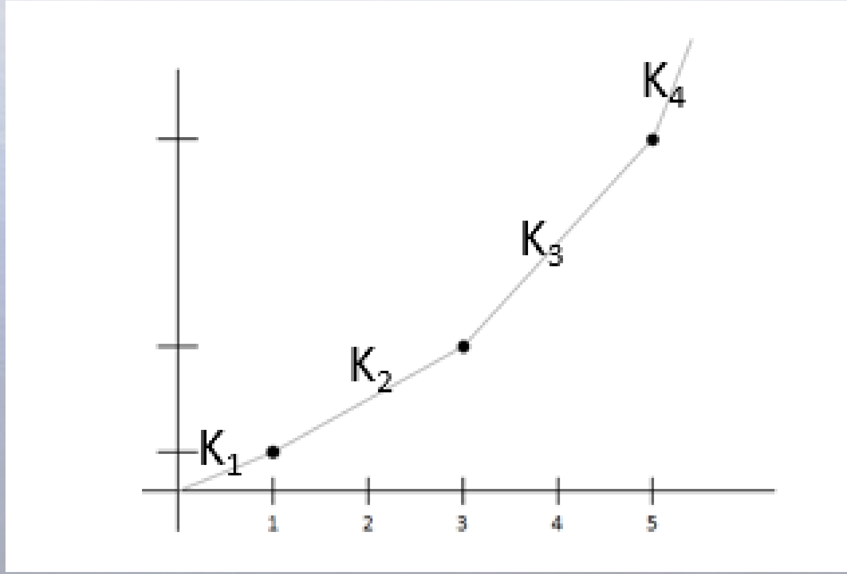


Applying Piecewise Linear to MPC

Nonlinearity



Piecewise Linear

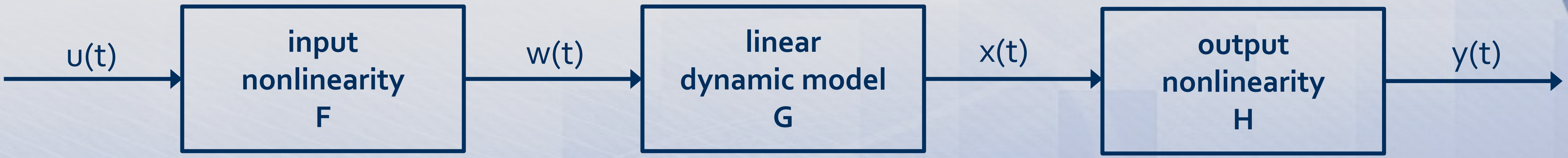


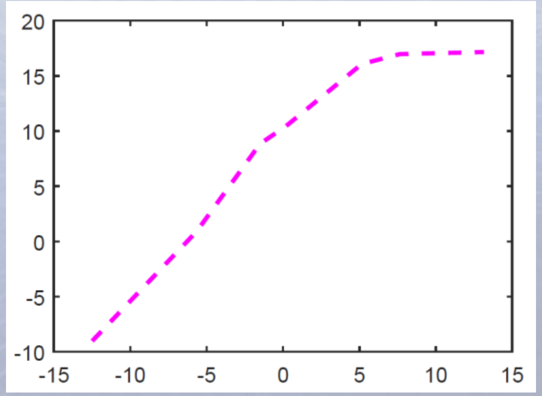
Nonlinear static element (Gain) and Linear dynamic element (Time Constant)

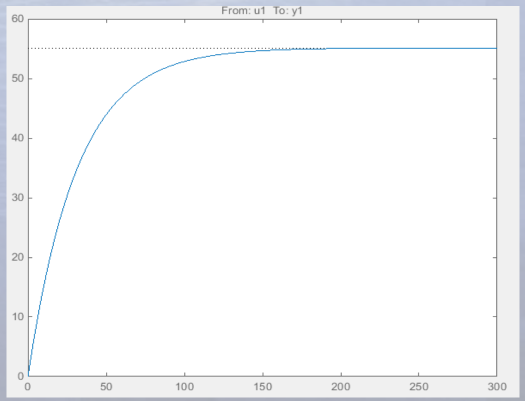
→ Assume that the variation of the dynamics is negligible.

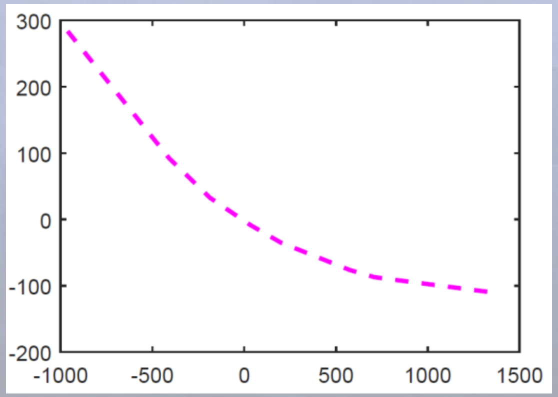
→ Time constant of Downhole pressure response is ~50 second.

Structure of Hammerstein-Wiener Models

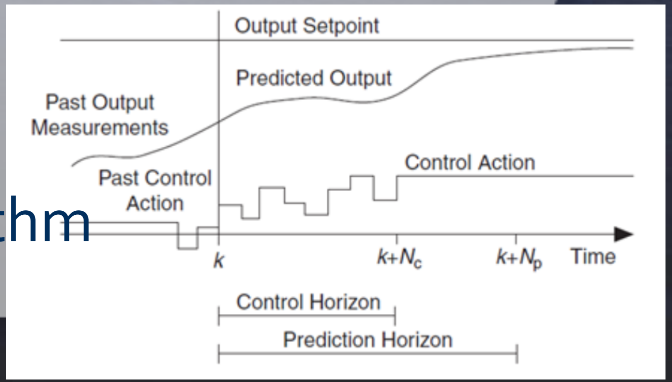




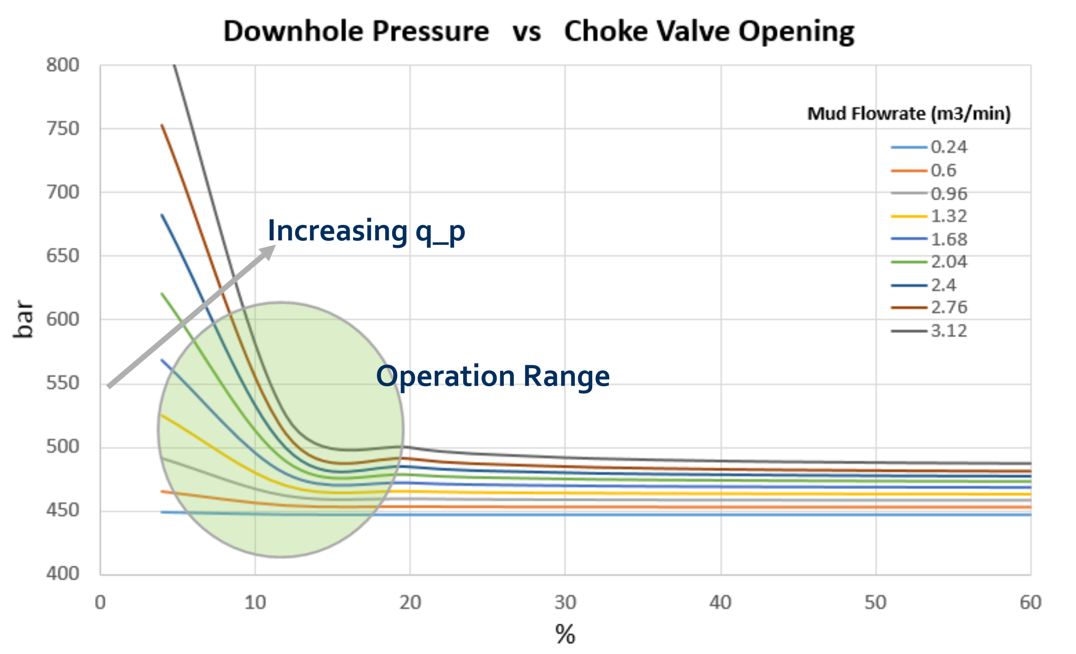


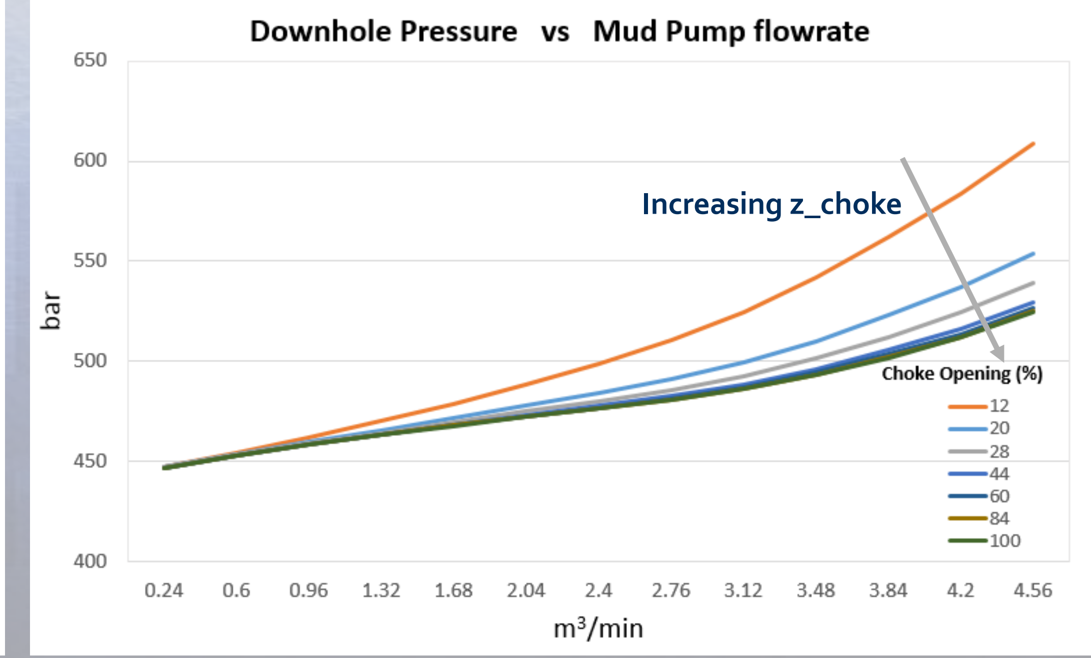


Transform the input and output instead of changing Gain directly.
Changing Gain will occur the prediction error.
Most efficient way to apply piecewise linear concept to MPC algorithm



Nonlinearity in MPD Process





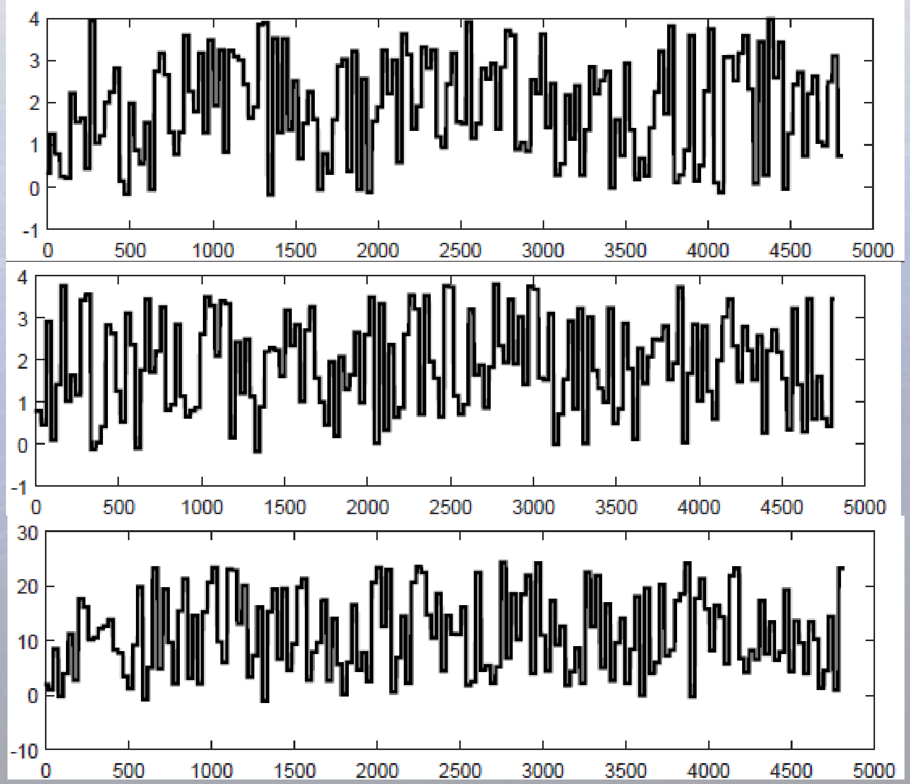
Model Identification – Hammerstein Wiener

Random Signal step test

Mud Pump flowrate

Back pressure Pump flowrate

Choke opening

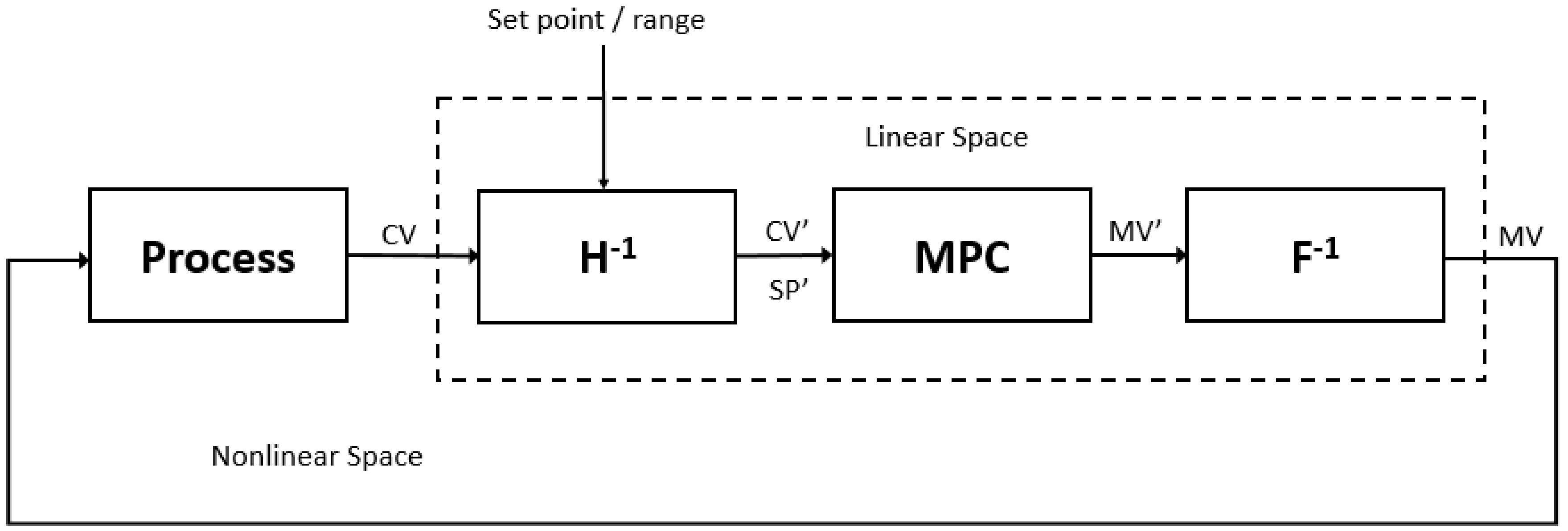


- Cover the entire operation range of interest to get nonlinearity.

- Implementing Multi Variable Identification

  3 input nonlinearity blocks
  3 Linear Model blocks
  1 output nonlinearity blocks

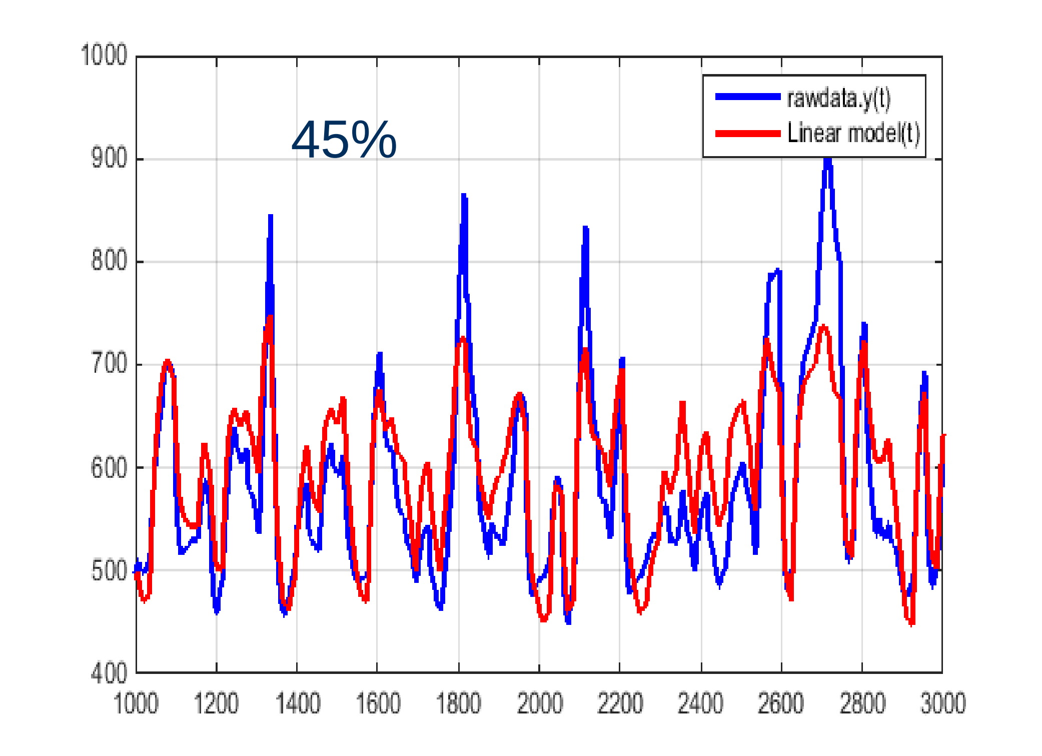
Structure of Hammerstein-Wiener MPC

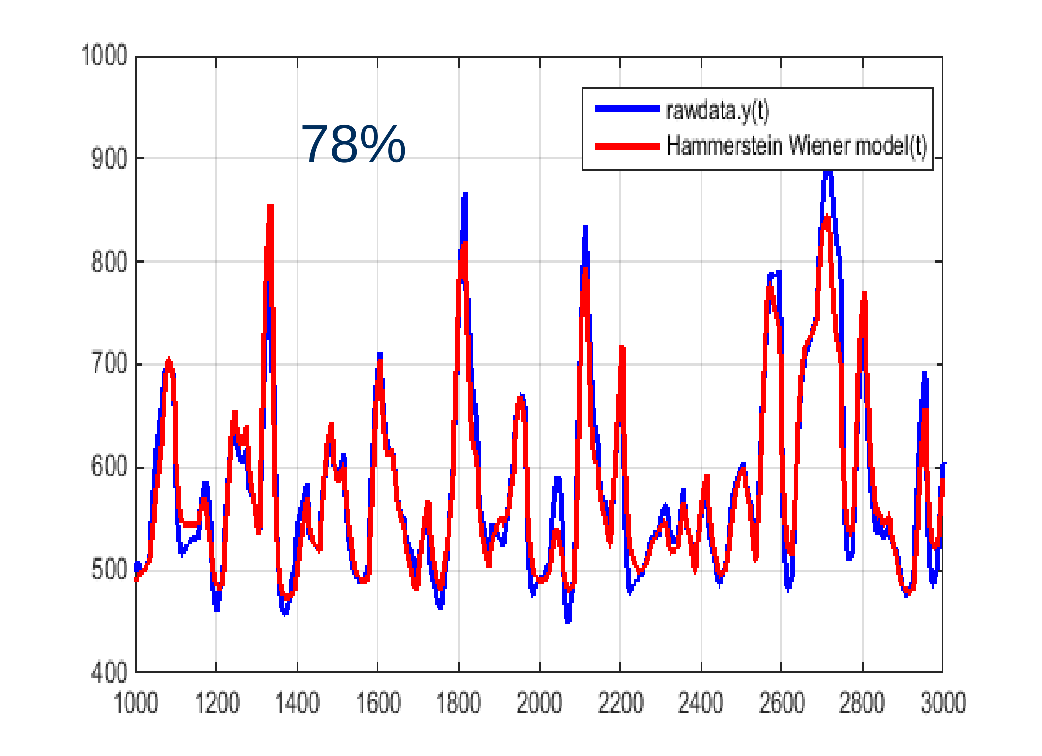


H^{-1} : Transposed output nonlinearity
F^{-1} : Transposed input nonlinearity
CV' : Transformed control variable
MV' : Transformed control variable
SP' : Transformed control variable

Model Validation - 1

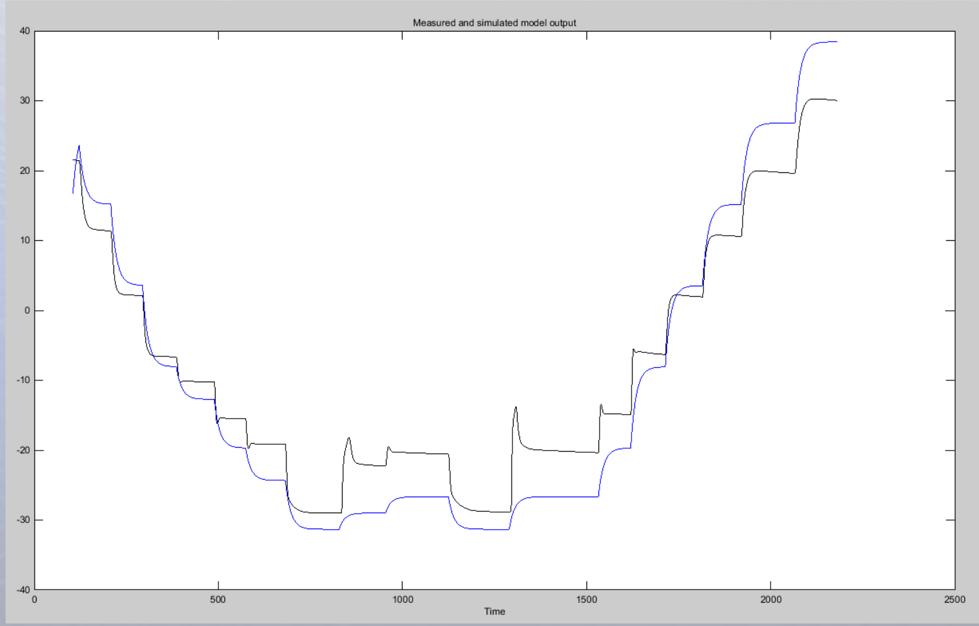
Linear Model vs Hammerstein Wiener Model

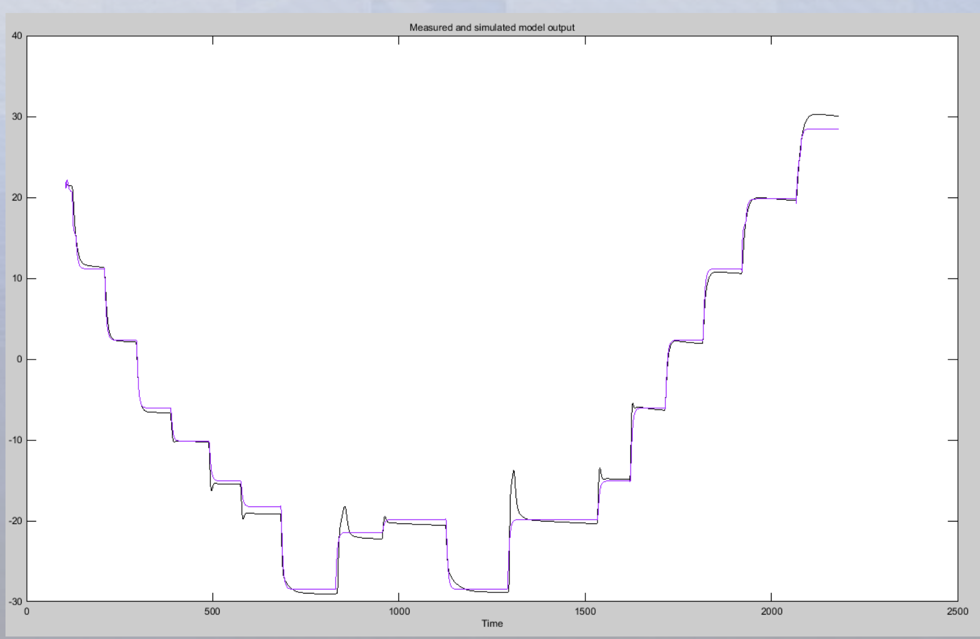




Model Validation - 2

Linear Model vs Hammerstein Wiener Model





Conclusion

- Estimate the downhole pressure by using Lower Order Model

- Validate the control performance
  - Maintain pressure within 1 bar during Normal drilling
  - Improved Model accuracy up to 80% for Pipe connection

Future work

- Improve the Lower Order Model for downhole estimation
- Performance verification with high fidelity simulator for:
  - Kick attenuation
  - Cuttings build-up detection and removal
- MPD Rig Testing at NOV Navasota test facility

Acknowledgements

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  - **Adrian Snell**
  - **Andy Craig**
  - **Shantur Tapar**
  - **Alan Clarke**

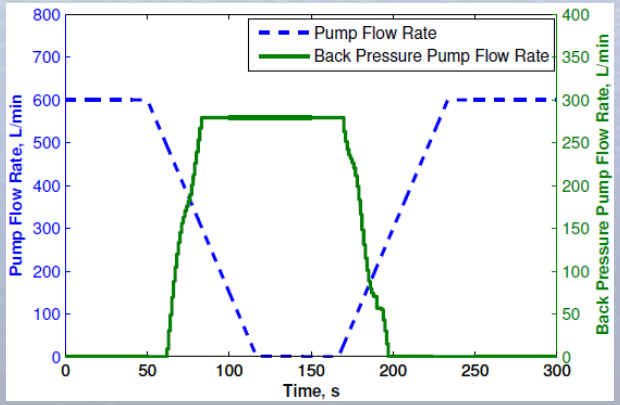
Questions?

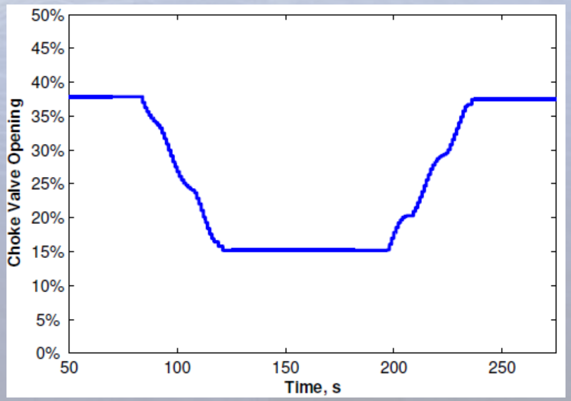
Back up slides

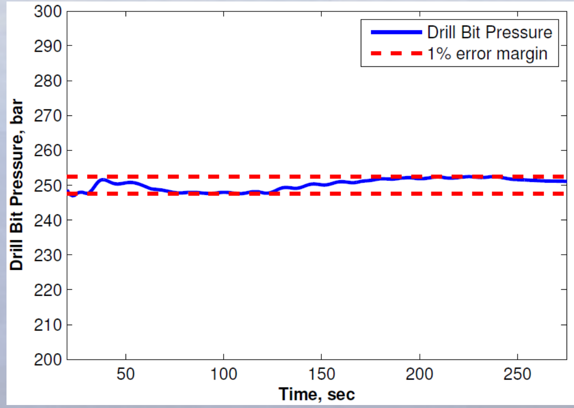
Pressure Controller Results

Normal Drilling:
- Estimator adapts within 1.5% error margin in 30 sec
- Drill bit pressure is controlled to set point

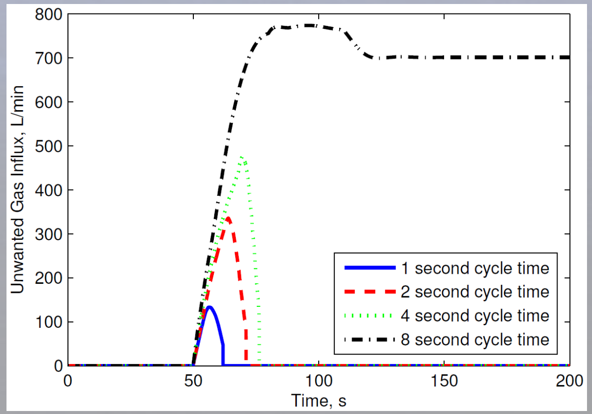
Connection Procedure:
- The controller is able to control the drill bit pressure +/- 3 bar





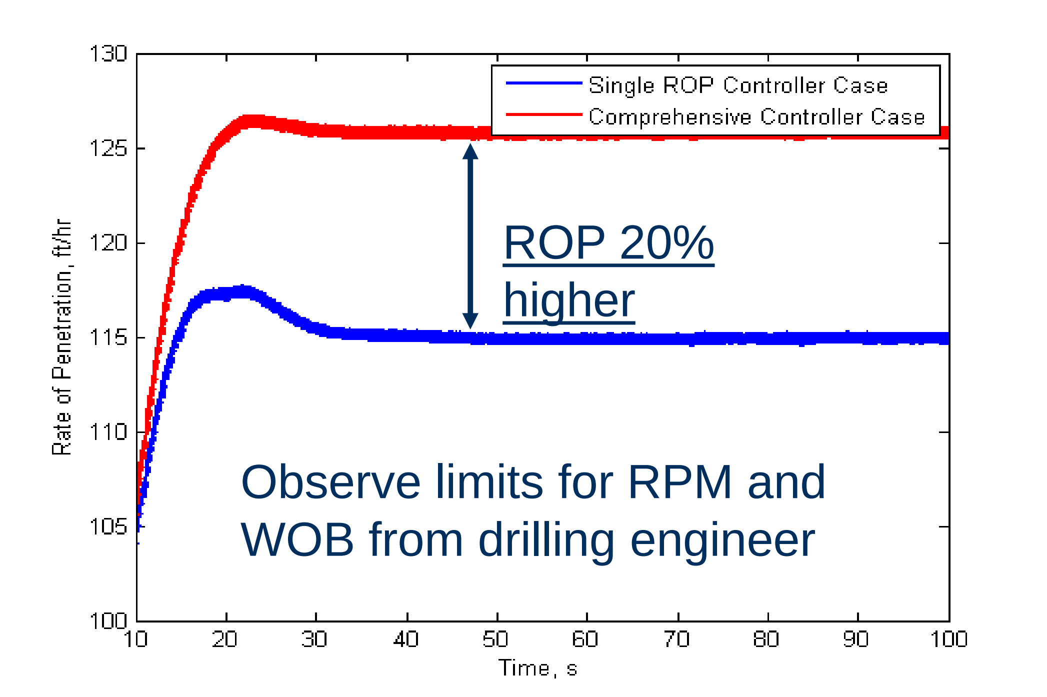


Kick Attenuation:
- Improved response to unexpected gas influx
- Immediate action avoids more intrusive well control efforts

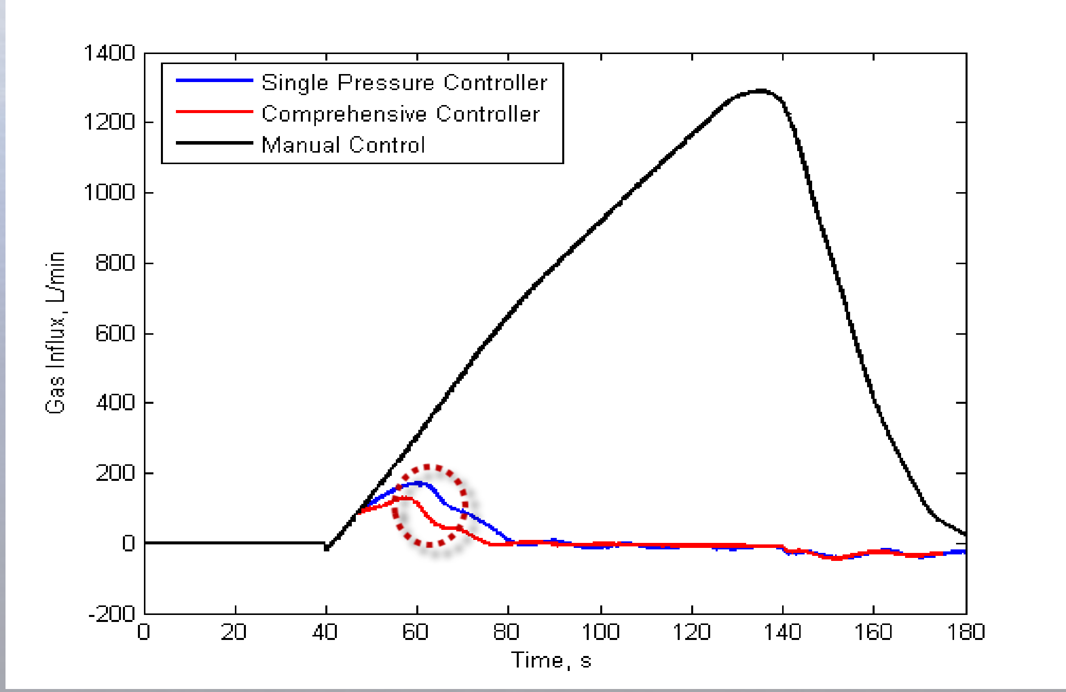


ROP and Downhole Pressure Control

- Increased ROP due to the decreased downhole pressure



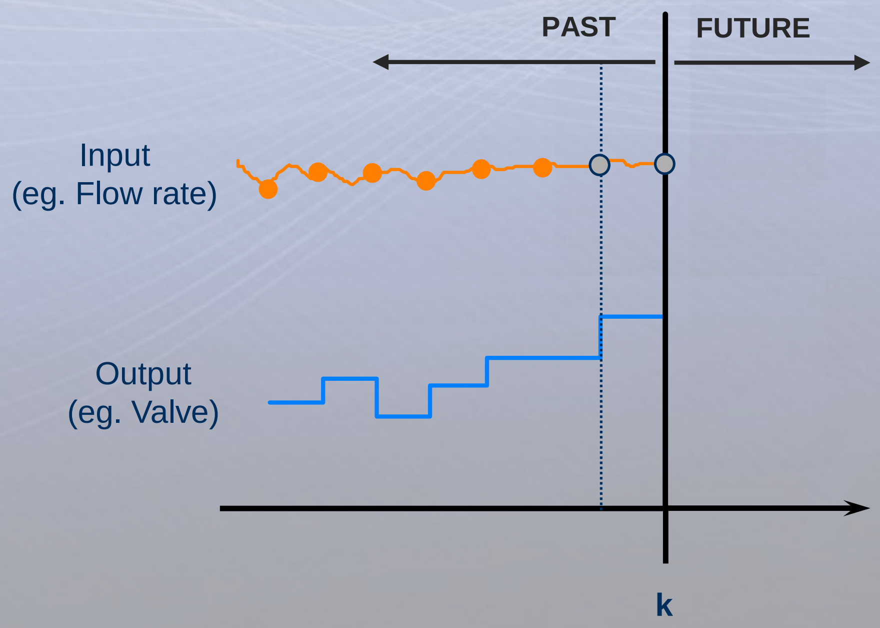
- Improved kick attenuation compared to single pressure controller



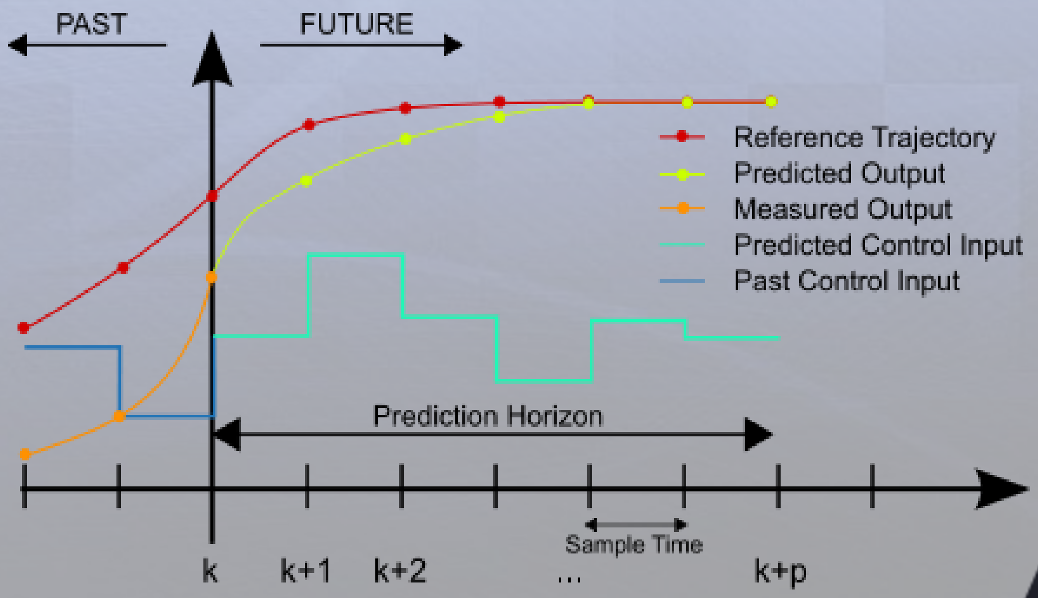
PID and Model Predictive Control

Model Predictive Control “sees” into the future to make an optimal moves of MV

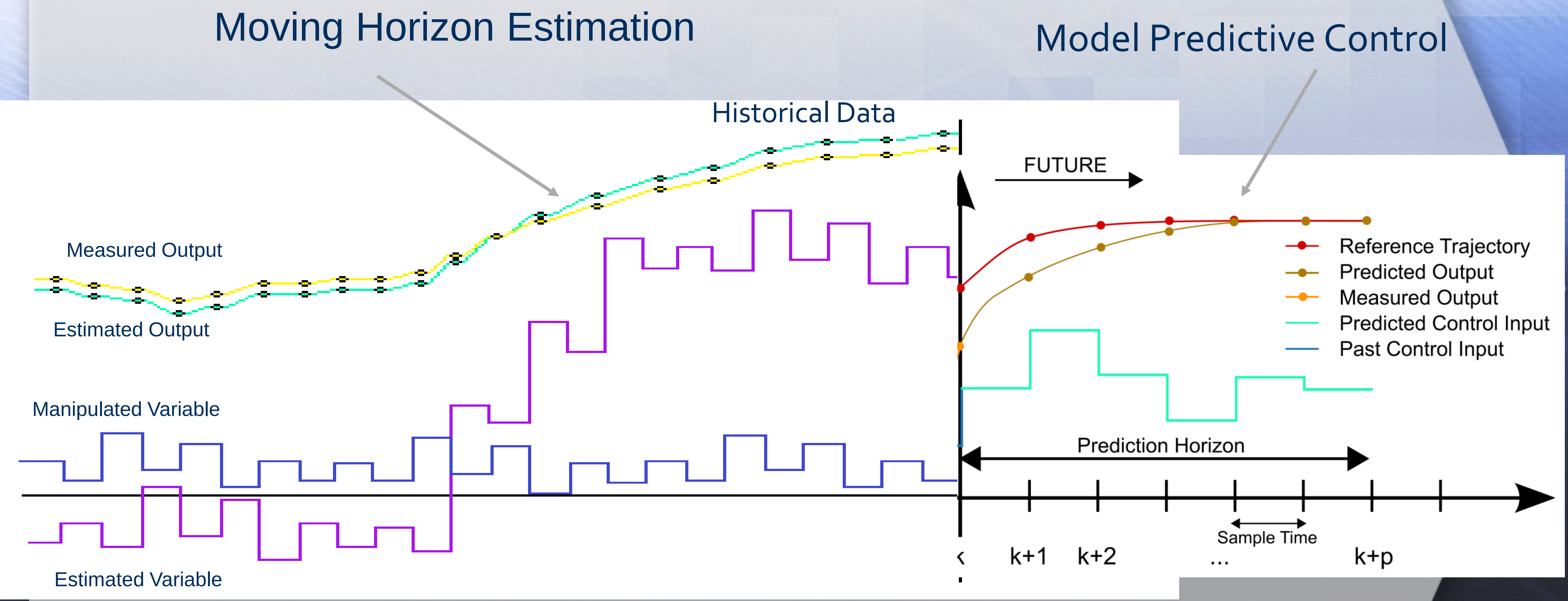
Conventional (PID)



Advanced (MPC)

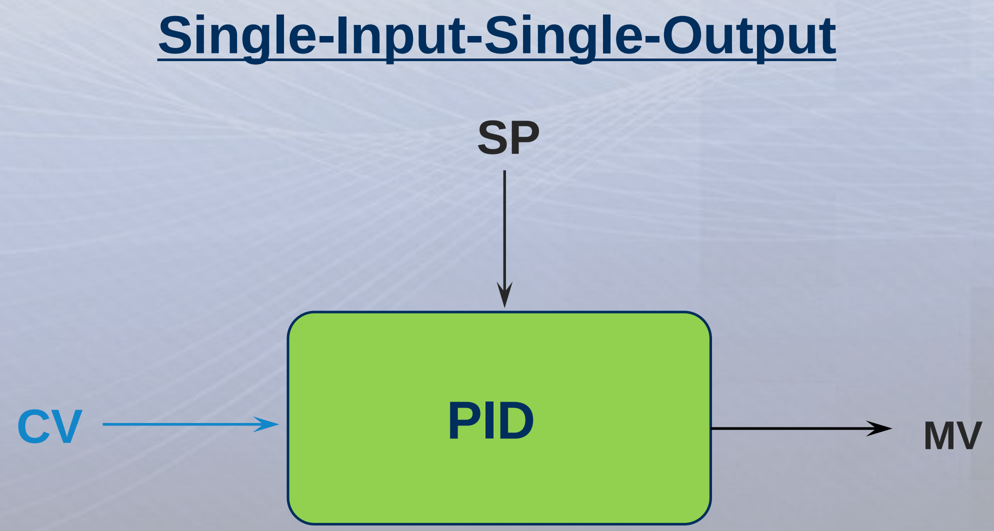


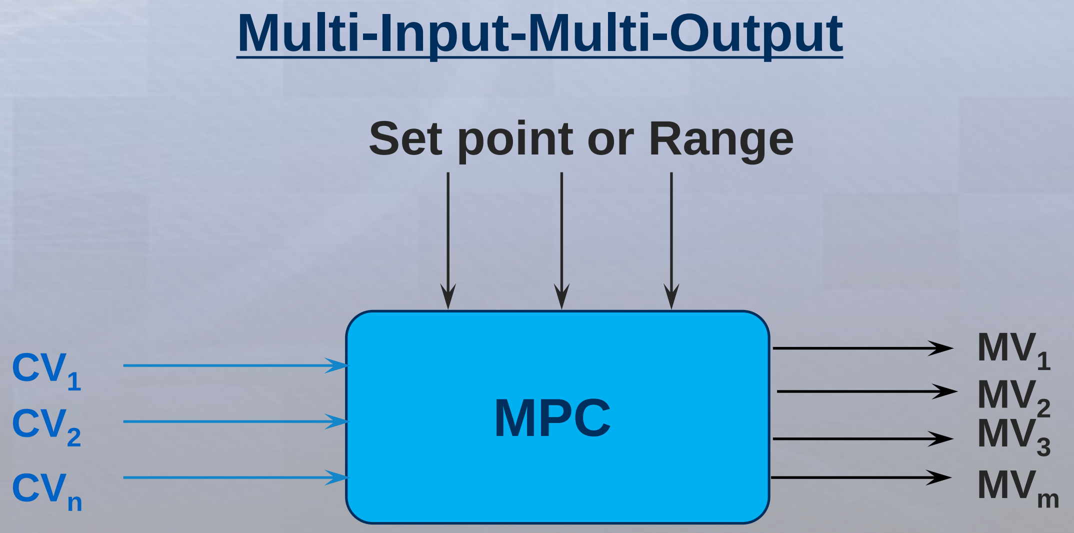
Models Adapt to Changes



PID and Model Predictive Control

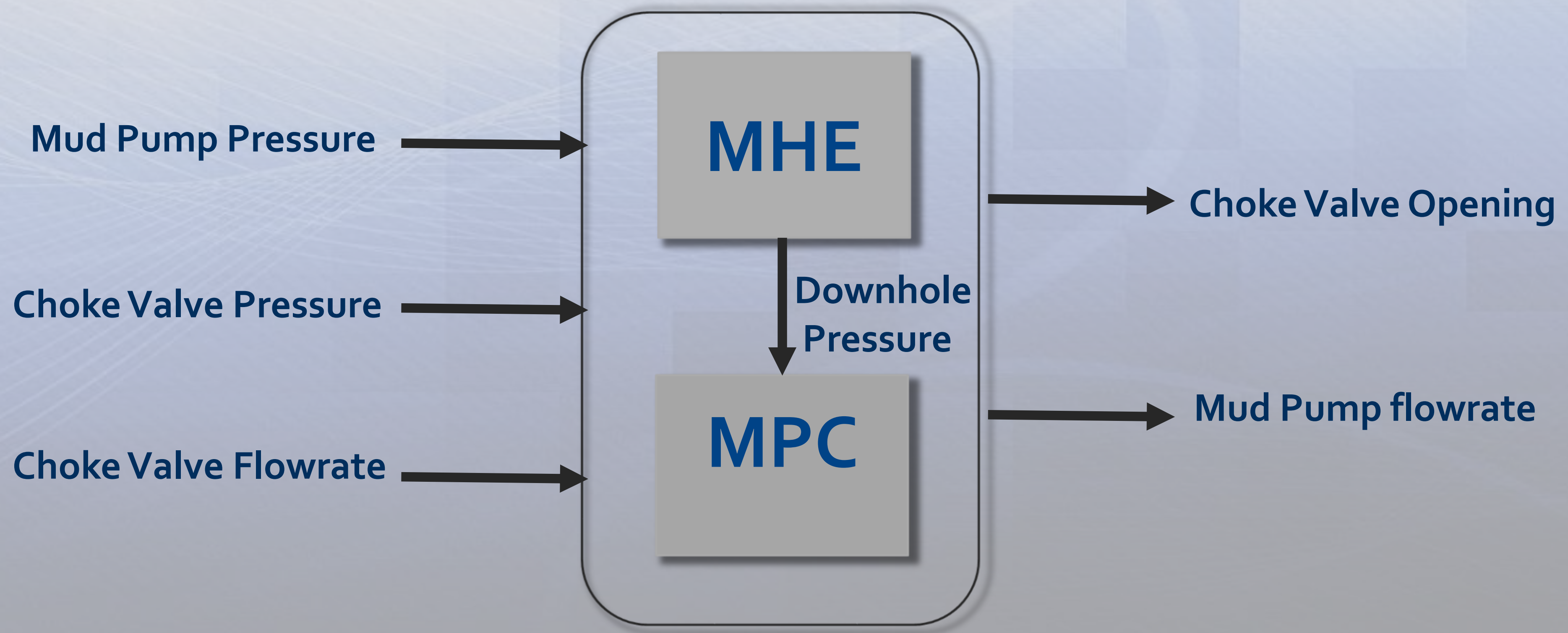
Multivariable control aspects





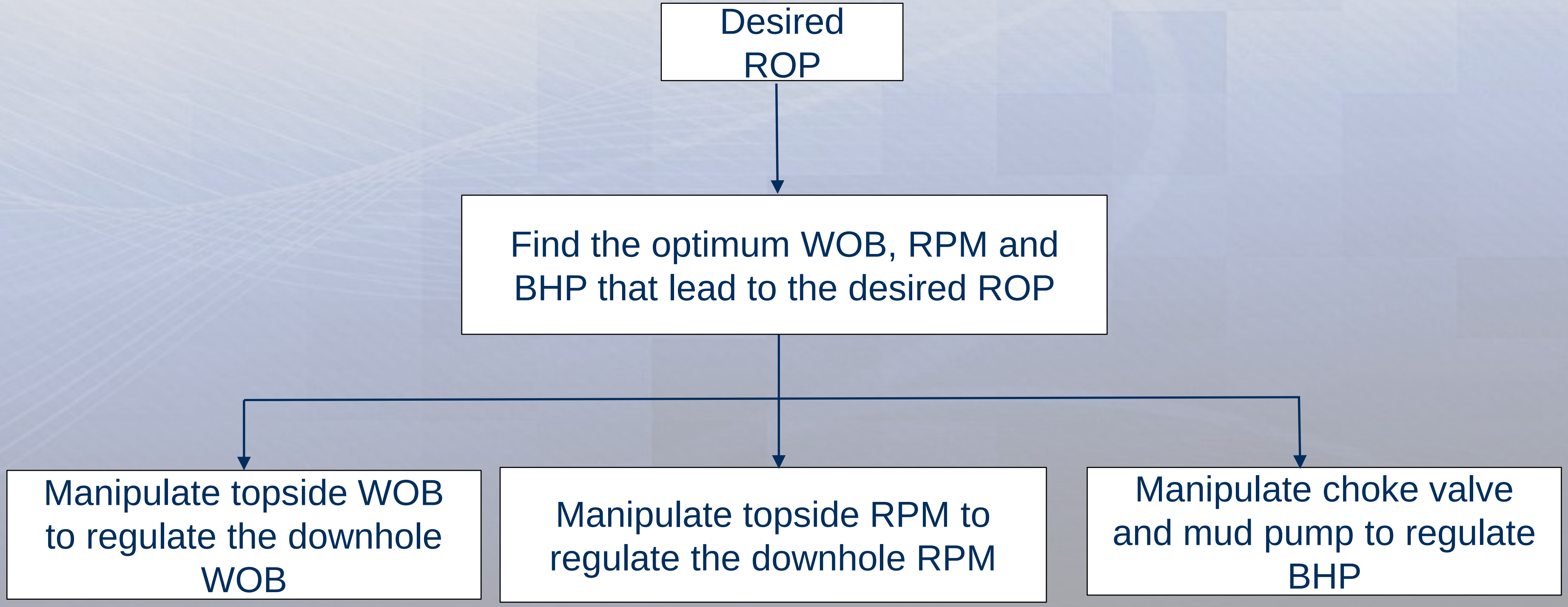
Control System Overview

Inputs and Outputs (Downhole pressure control)



Controller: Normal Operation

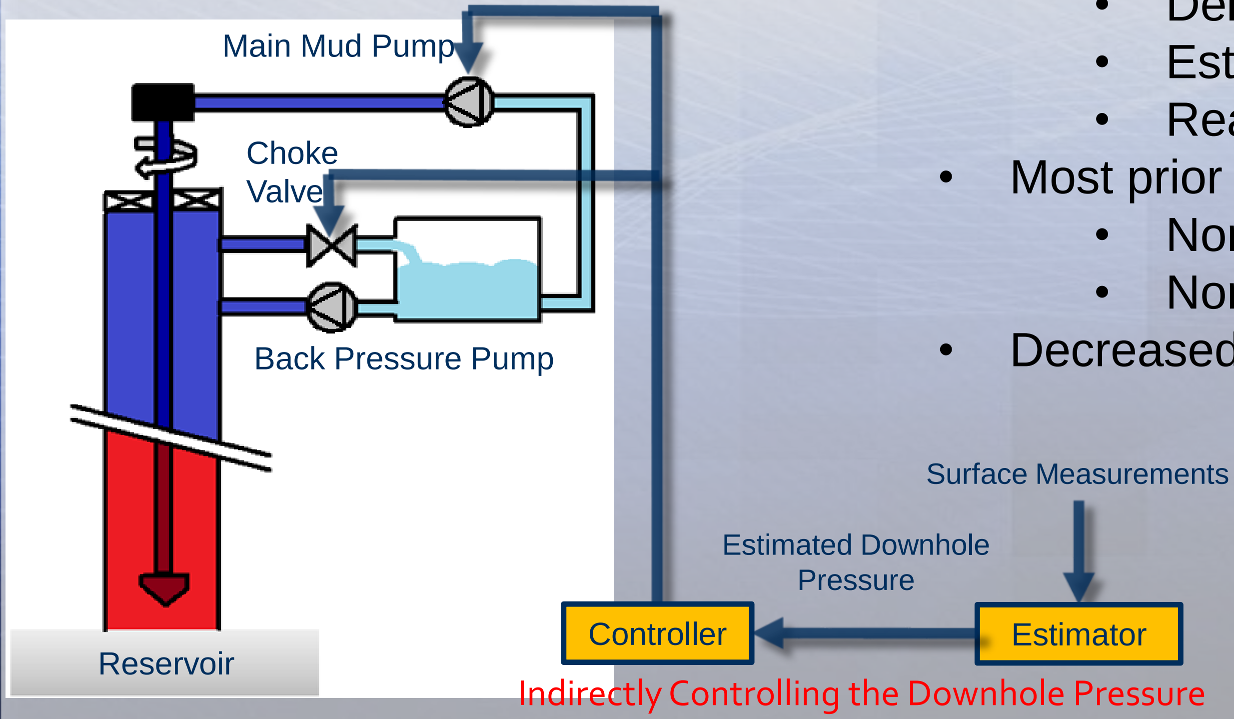
- **During normal operation, the optimum downhole pressure values are determined to give the highest possible ROP.**



Previous Work in Pressure Control

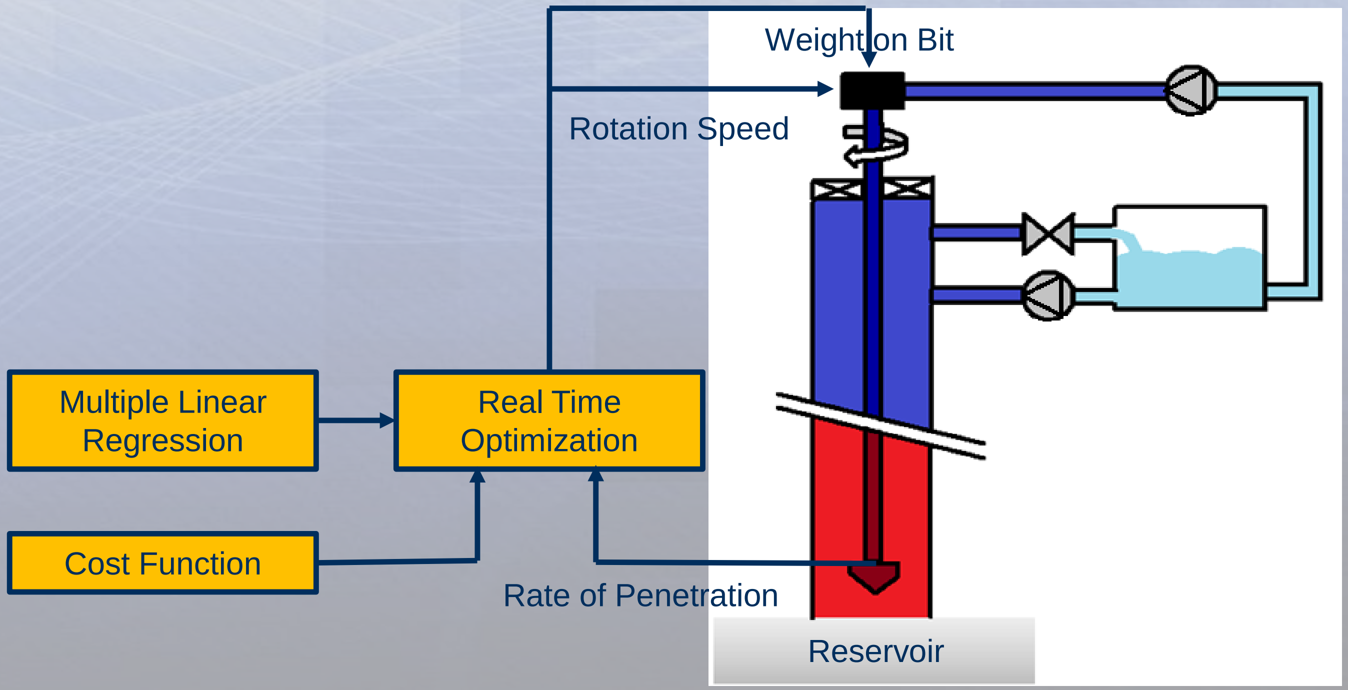
- **Using advanced technology which transmits pressure data to surface can improve pressure control**

- Surface measurements (without WDP)
  - Delayed response to kick events
  - Estimation of fluid properties difficult
  - Reactive pressure control vs. proactive
- Most prior work with linear controllers
  - Nonlinear viscoelastic mud properties
  - Nonlinear ROP effects
- Decreased and more variable ROP



Previous Work in ROP Control

- Ignore change of WOB and RPM along drill string
- Ignore effect of downhole pressure dynamics
- Potential for ROP improvement



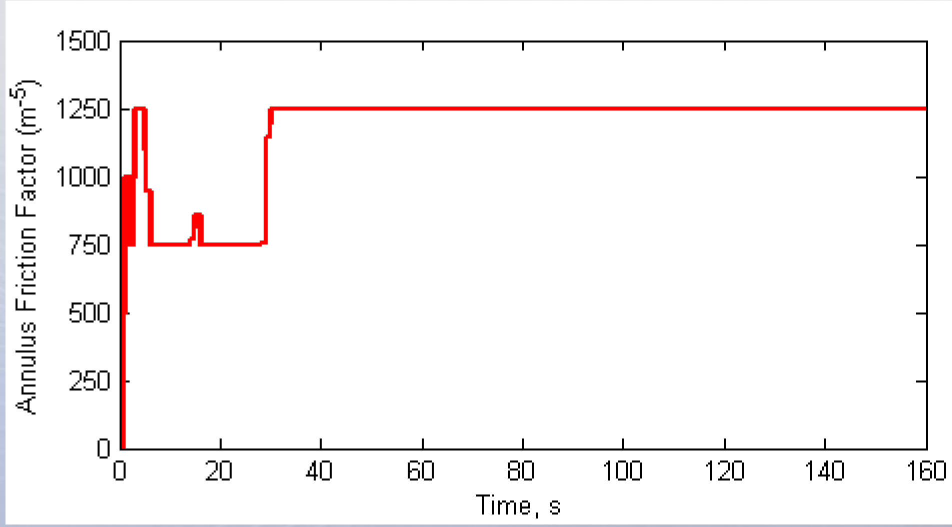
Model Components

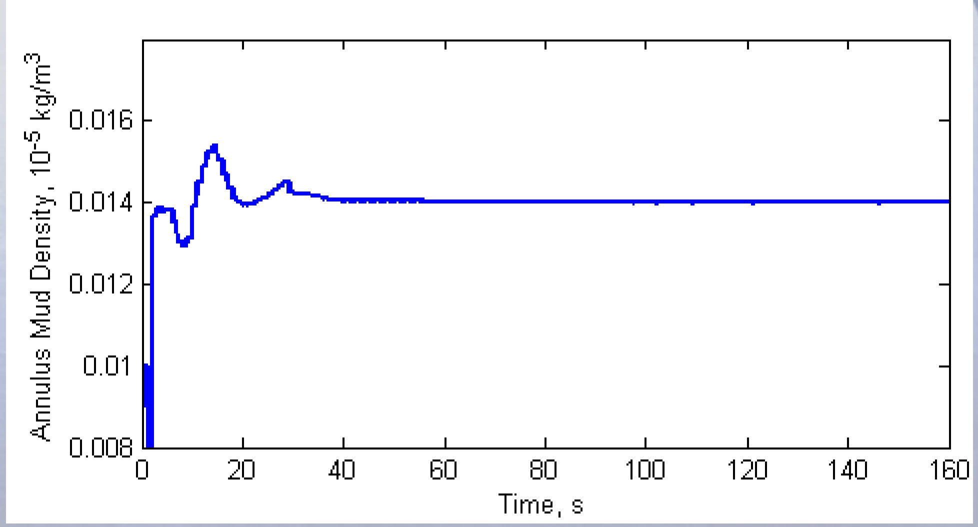
- Pressure Hydraulics: Lower order model (Stames et al.)
  - 4 state equations:
    - Mud pump pressure (pp)
    - Choke valve pressure (pc)
    - Drill bit flow rate (qbit)
    - Drilling height (h)

- ROP: Bourgoyne & Young model
  - 8 functions:
    - Formation strength
    - Pressure differential of bottom hole
    - Formation compaction
    - Bit diameter and weight
    - Rotary speed
    - Tooth wear
    - Hydraulics

$$ROP = exp\left(a_1 + \sum_{i=2}^{8} a_i x_i\right)$$

Single Pressure Controller MHE

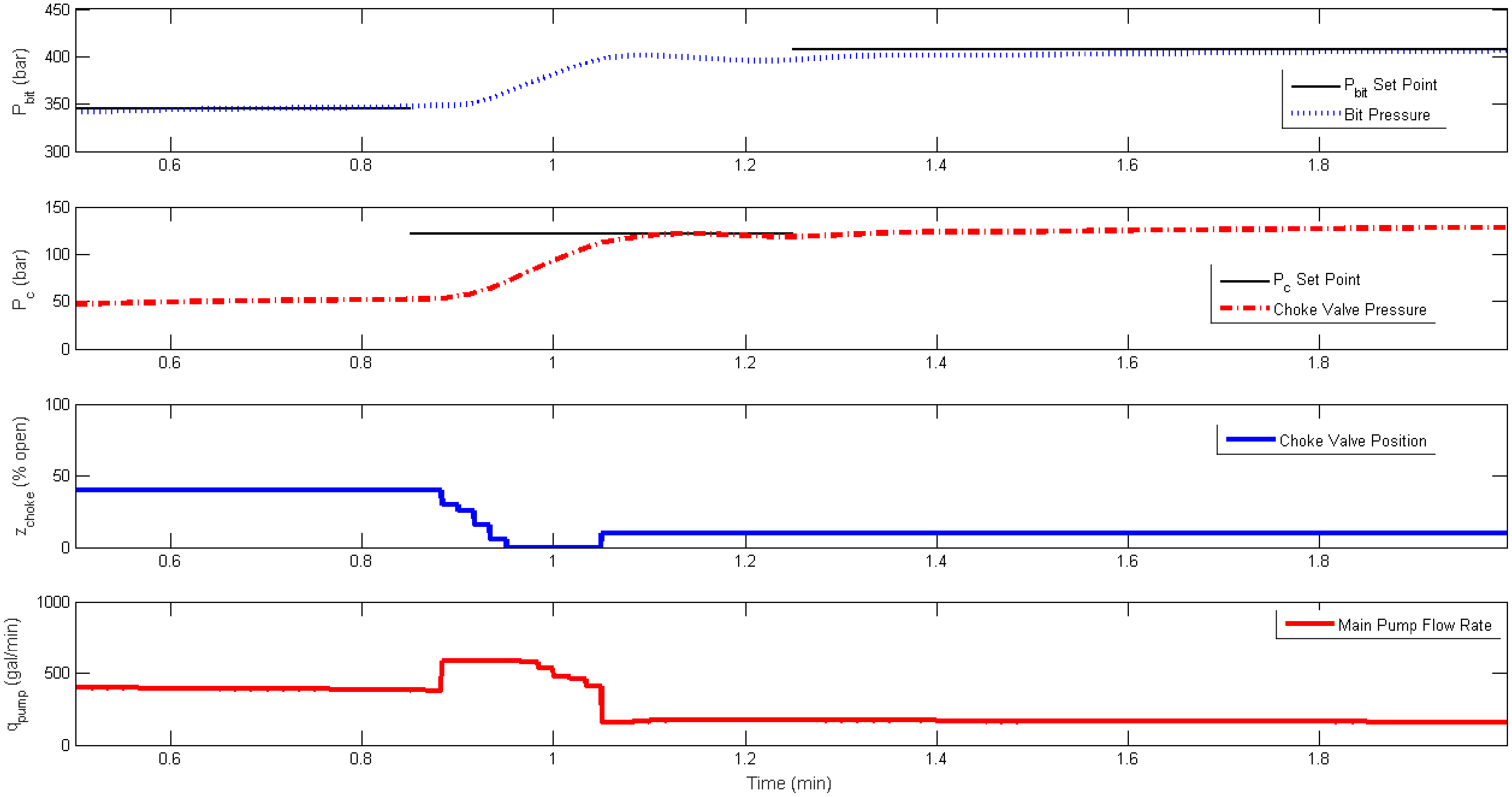




- Within 30 seconds of operation, the estimator accurately determines the friction factor and the annulus density within 1.5% of the actual value.

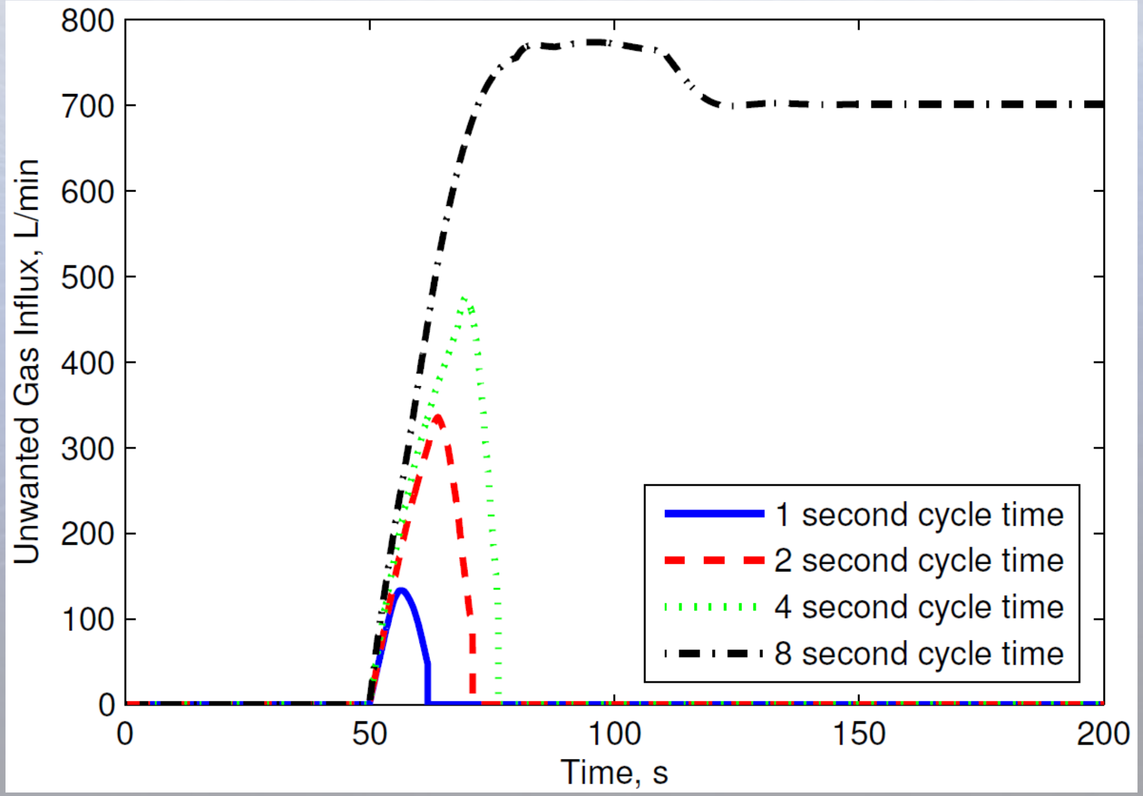
Pressure Control with Normal Drilling

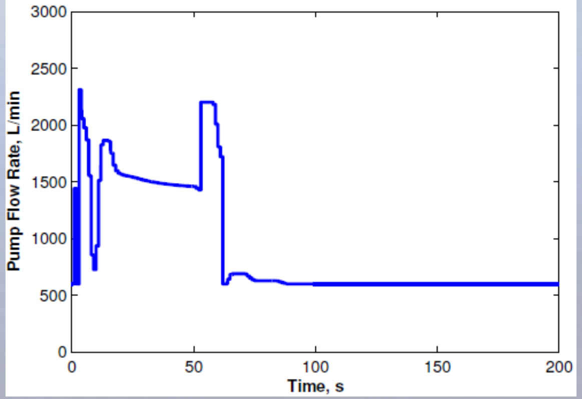
- Within 30 seconds, the drill bit pressure has been controlled within 0.72% of its set point of 345 bar

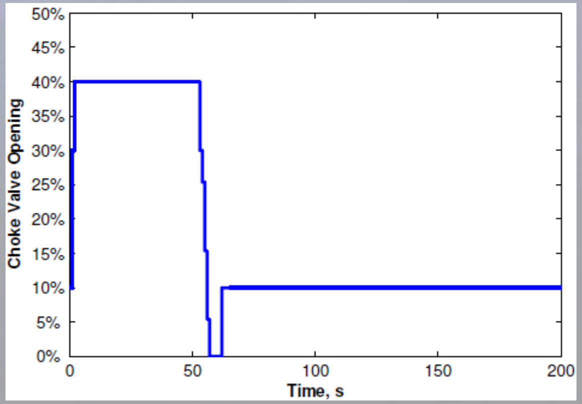


Kick Attenuation

- Improved Response to Unexpected Gas Influx.
- Immediate action avoids more intrusive well control efforts.

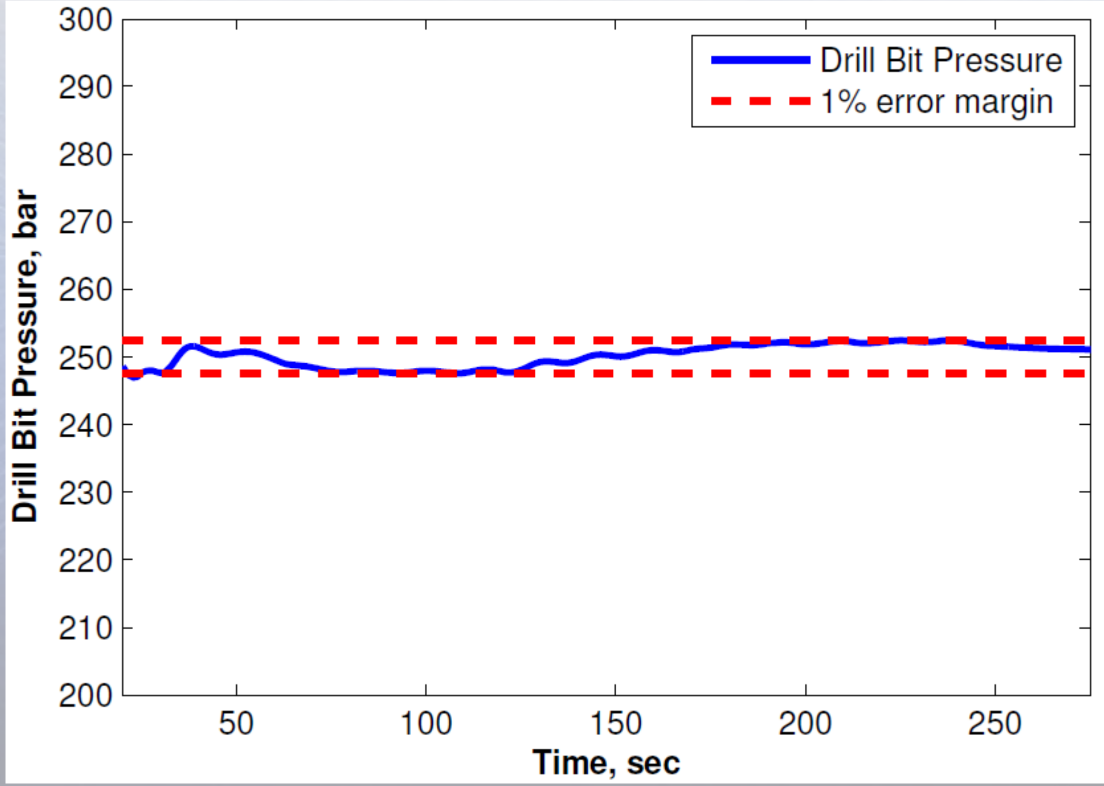


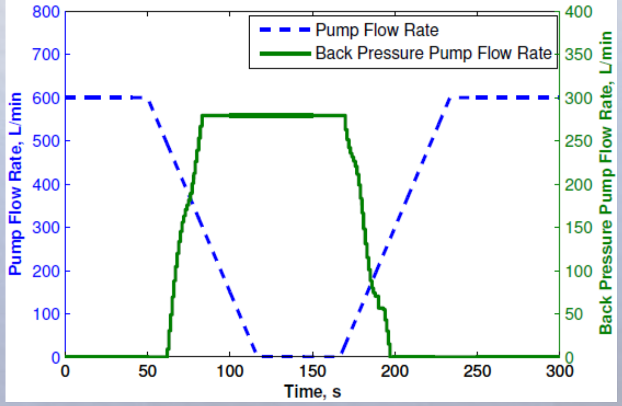


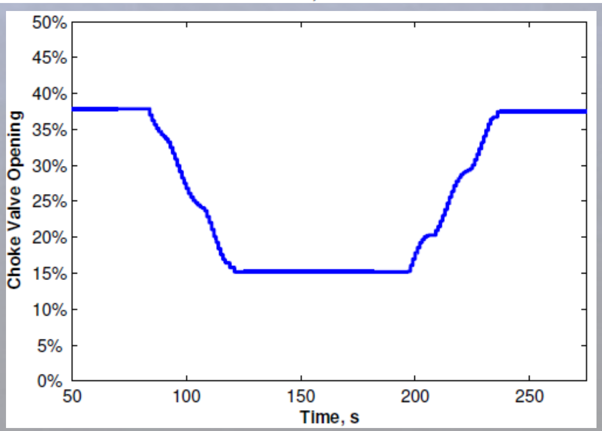


Connection Procedure

- The controller is able to control the drill bit pressure within 1% error margin.





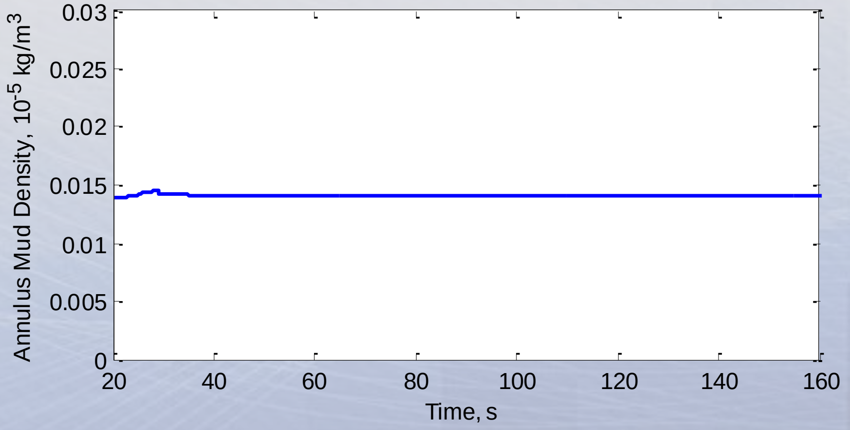


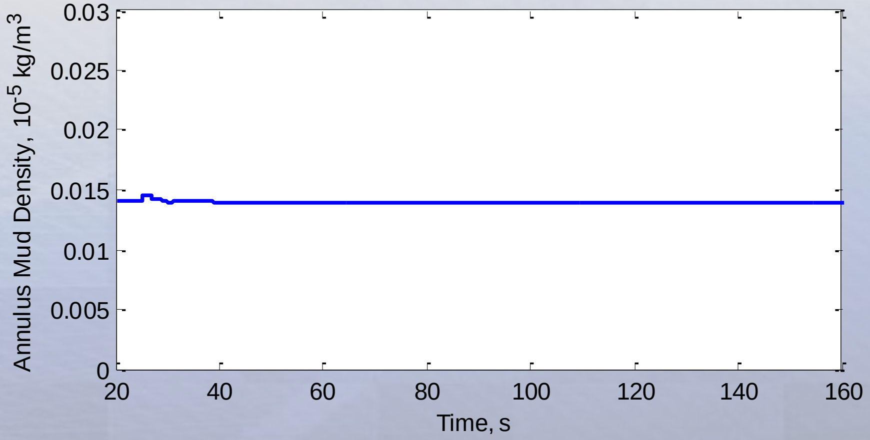
Estimator Performance

Squared Error

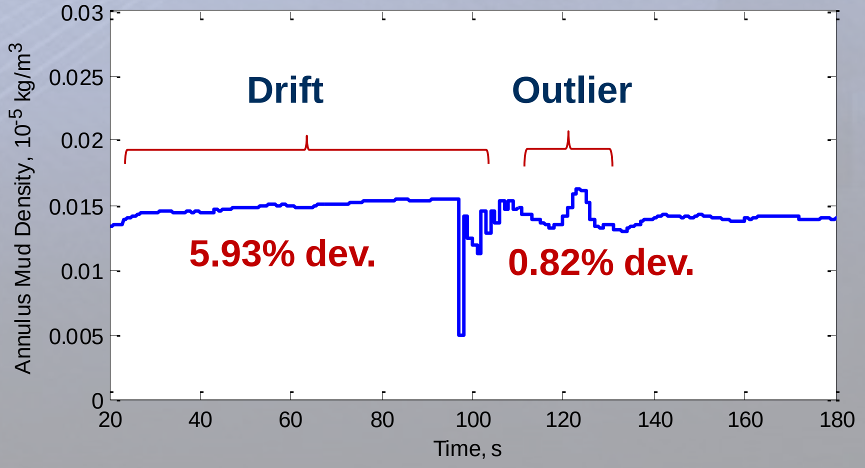
ℓ1-norm

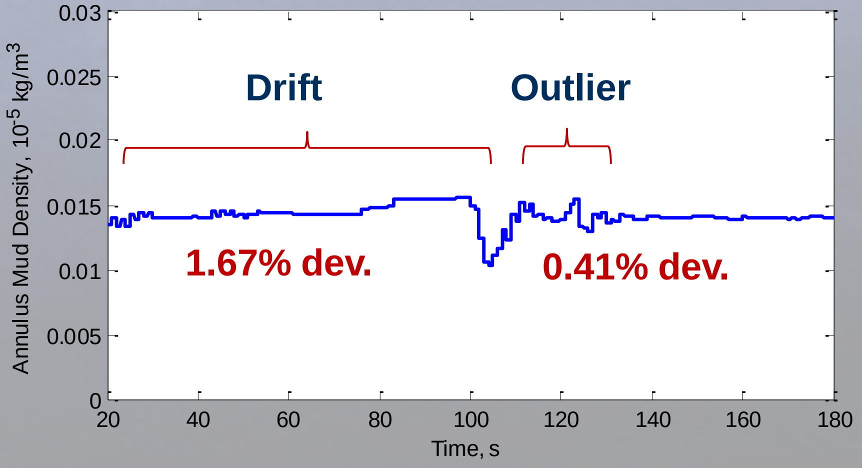
Clean Data





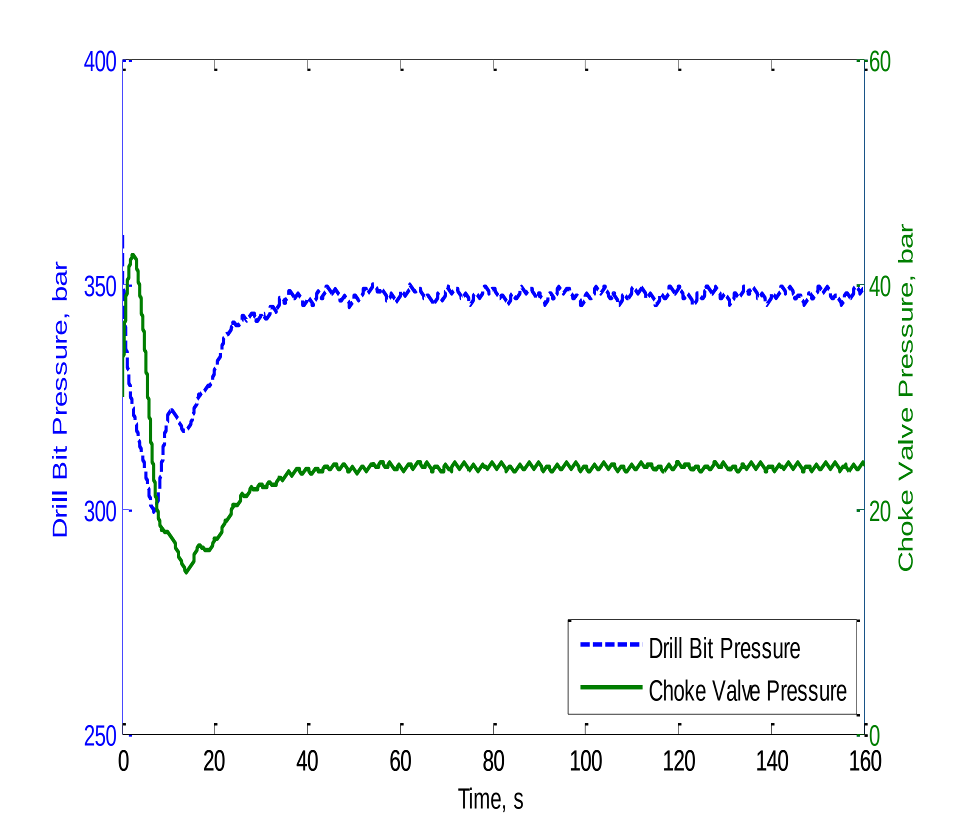
Corrupted Data



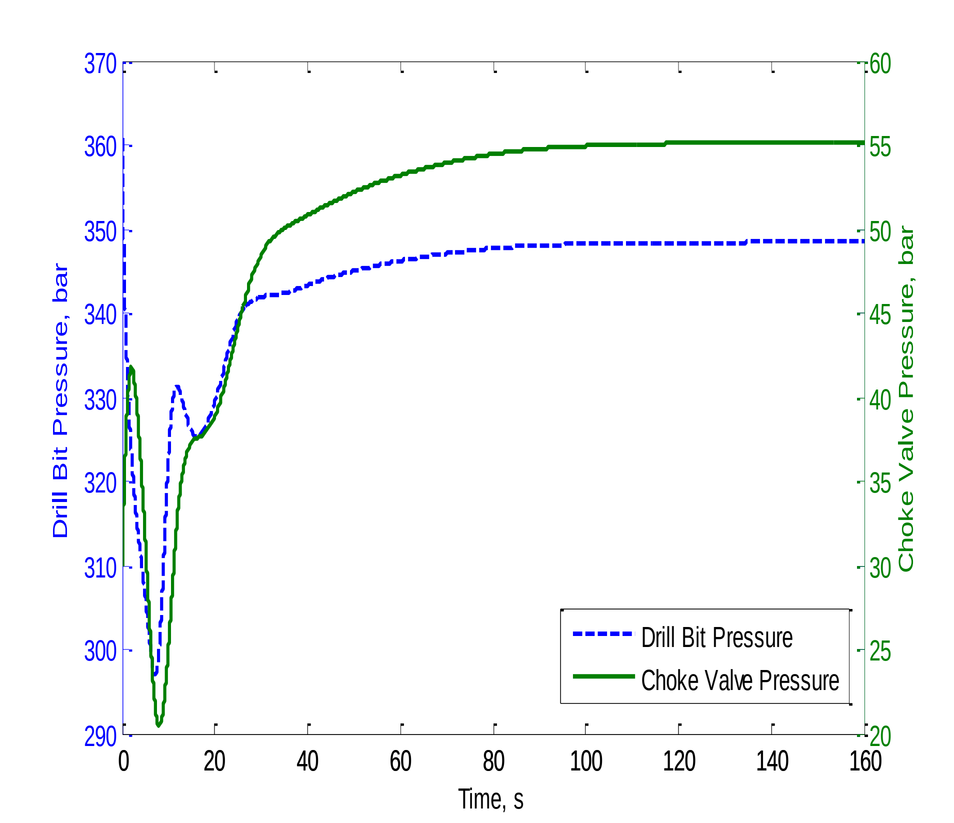


MPD Controller Performance

Squared Error

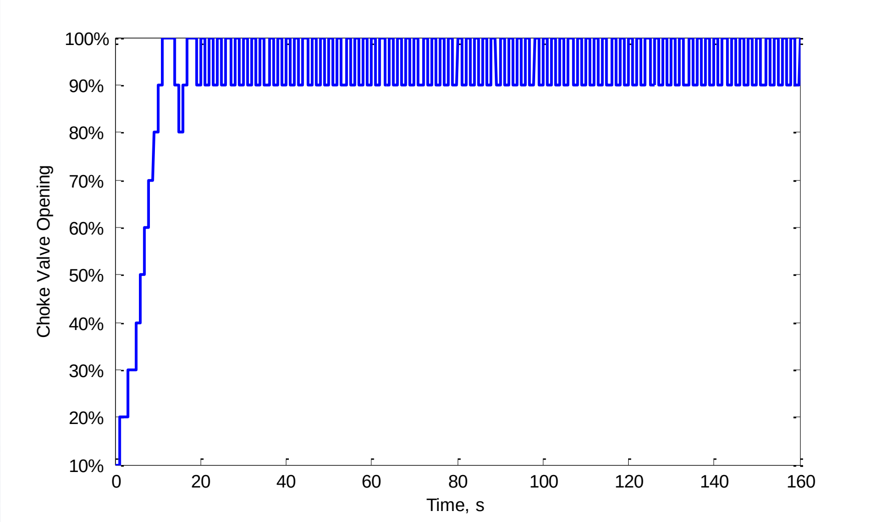


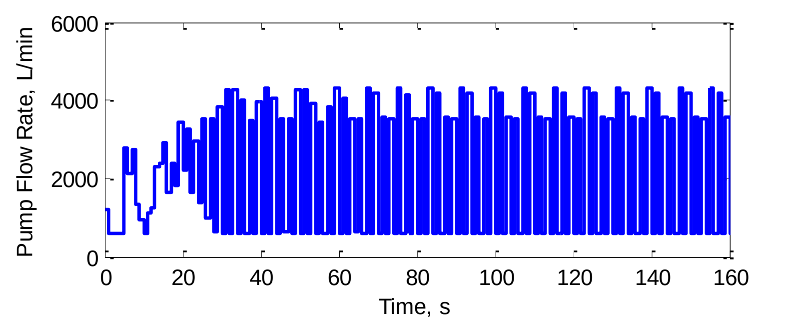
ℓ1-norm



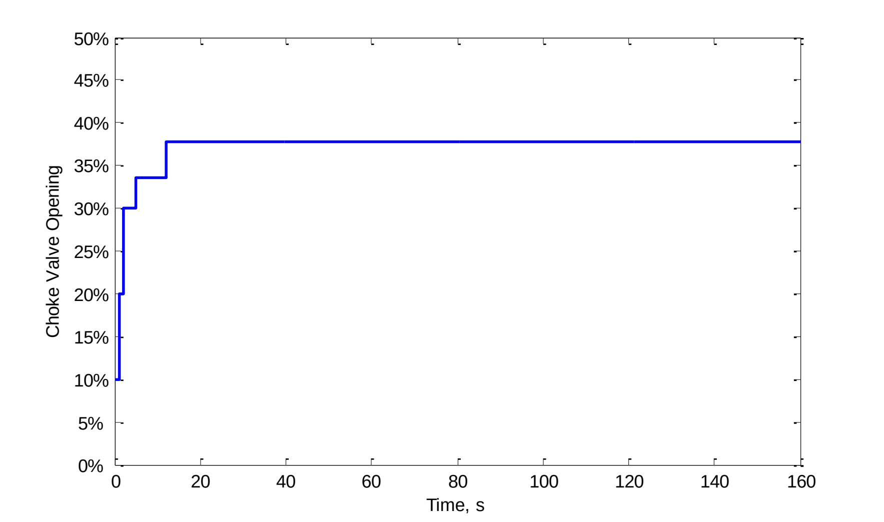
MPD Manipulated Variables

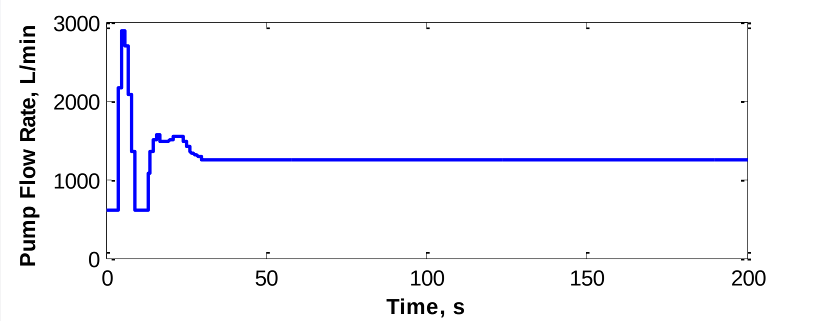
Squared Error





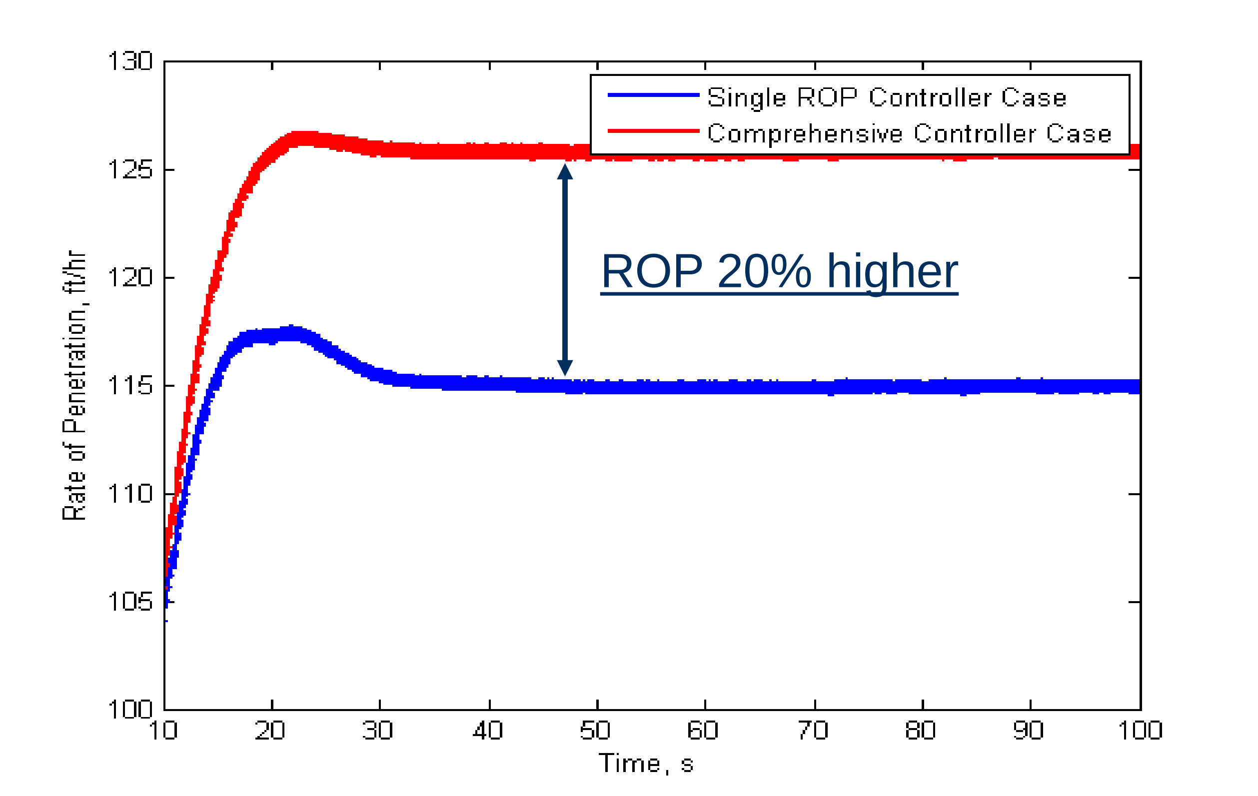
ℓ1-norm





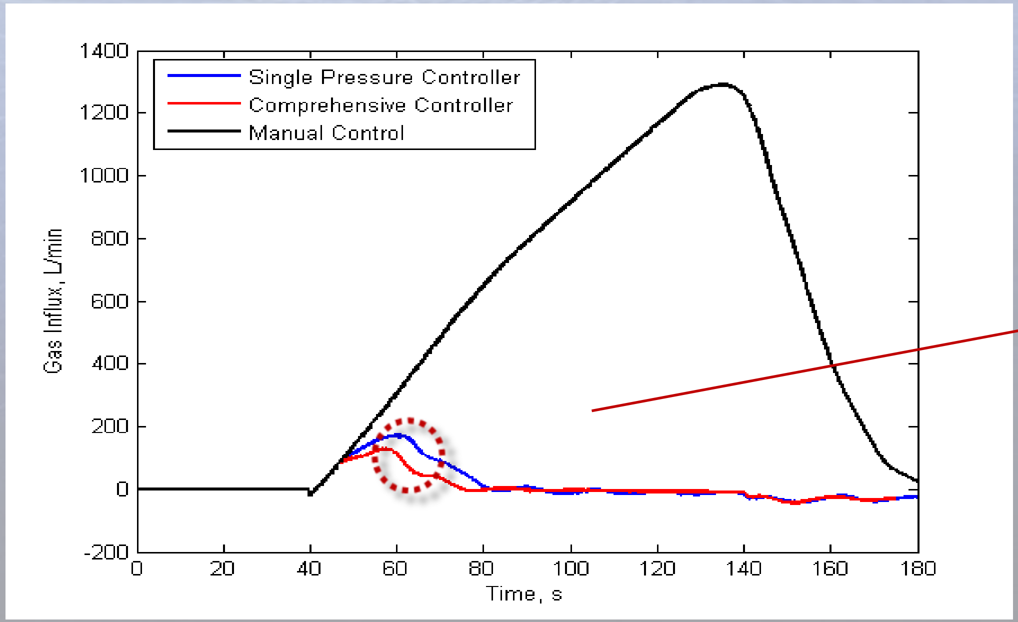
ROP Benefit

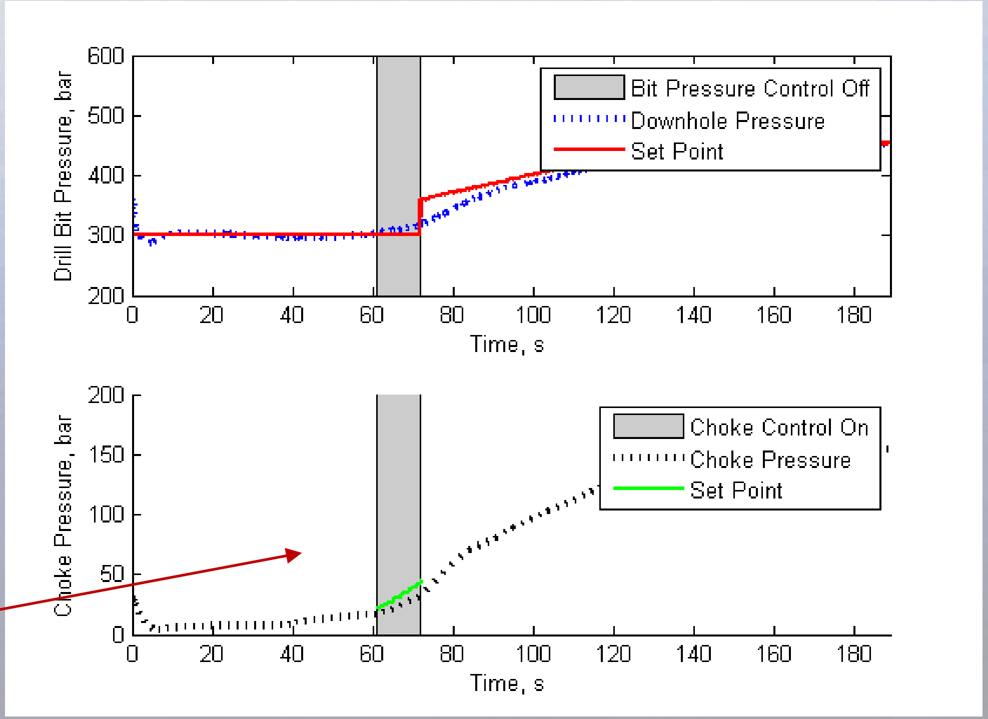
- Increased ROP due to the decreased downhole pressure.



Kick Attenuation

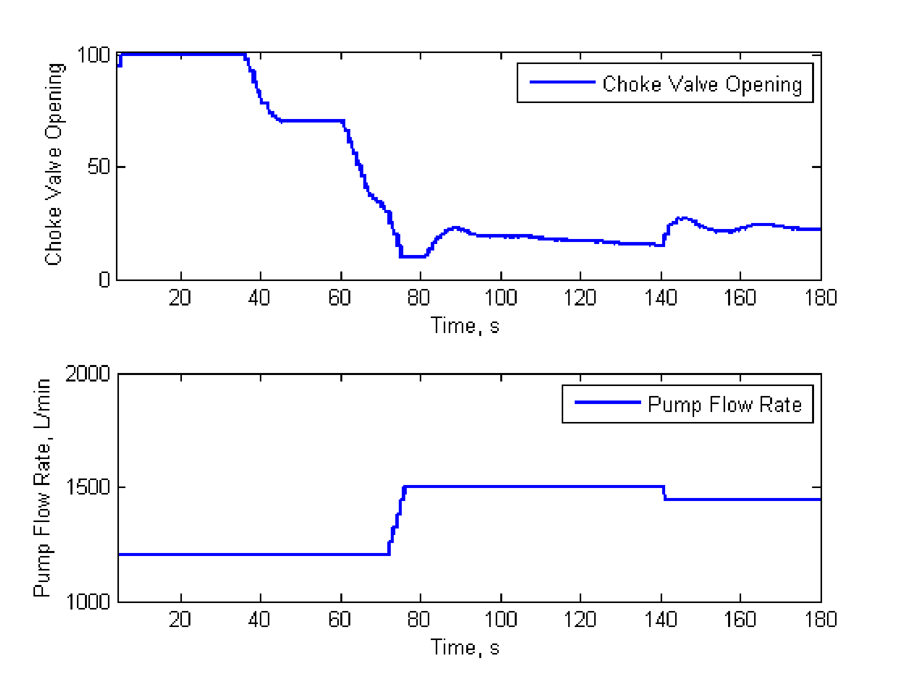
- Comprehensive controller is able to attenuate kick more effectively and faster compared with single pressure controller.

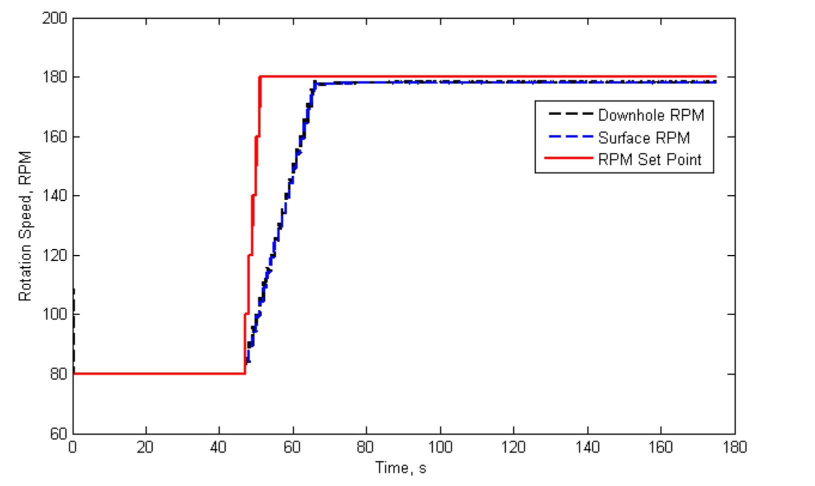


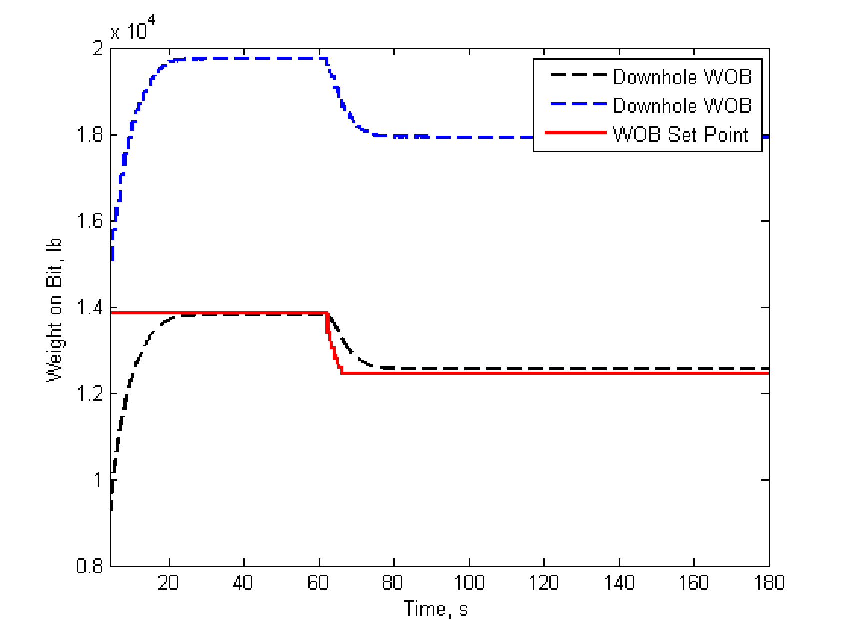


Kick Attenuation

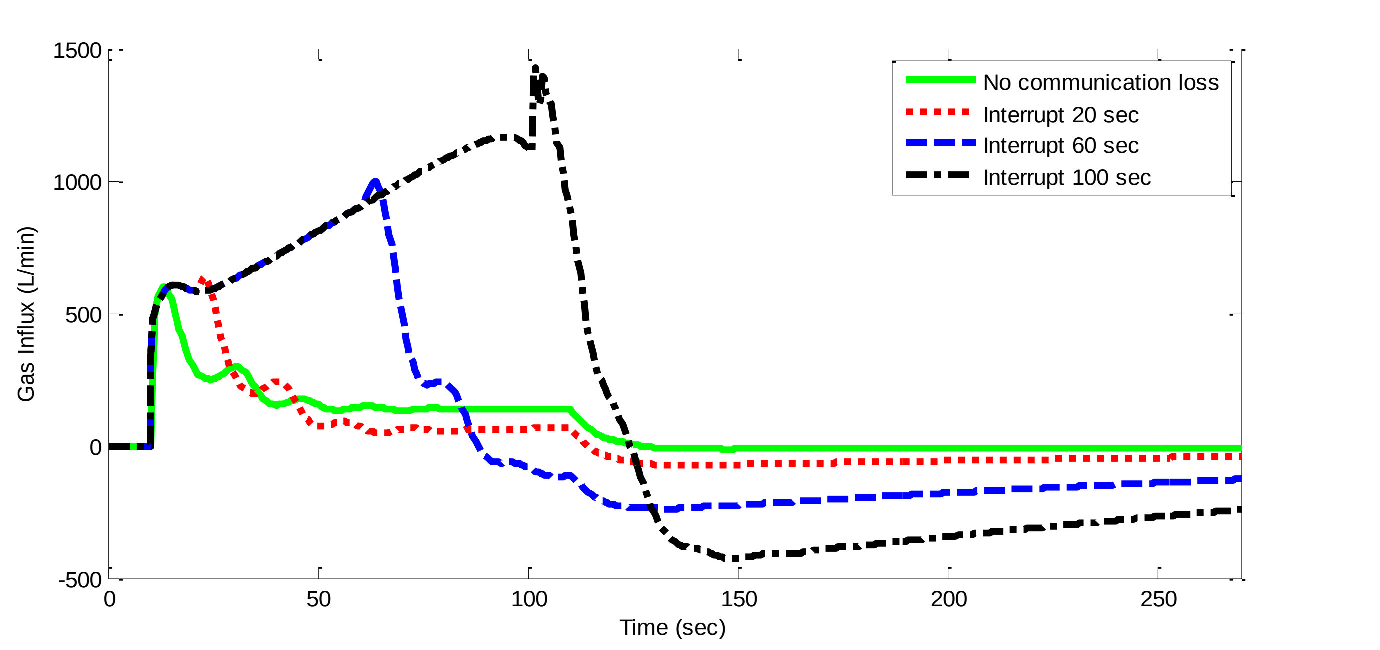
- Drilling continues with consistent ROP during kick.
- Avoids cutting loading issues due to ROP fluctuations.





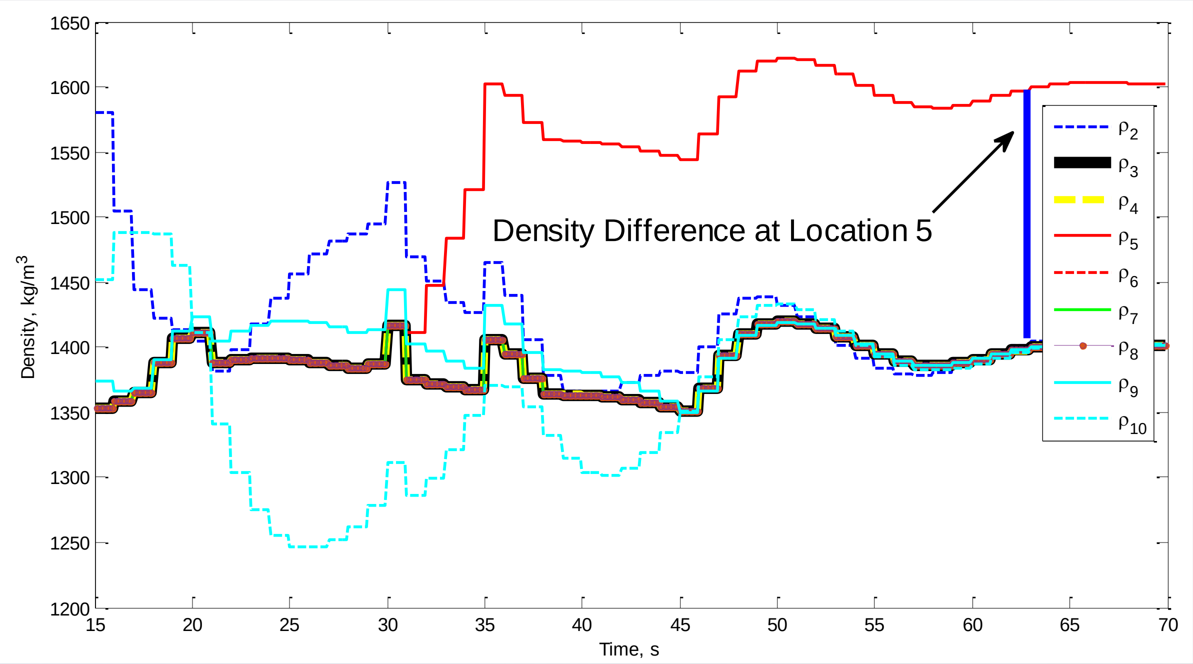


Surge/Swab Induced Kick



- Clear benefit in reducing the time that communication is lost with downhole pressure measurements.
- Automatic model-based controller is able to reject significant events of unexpected gas influx.

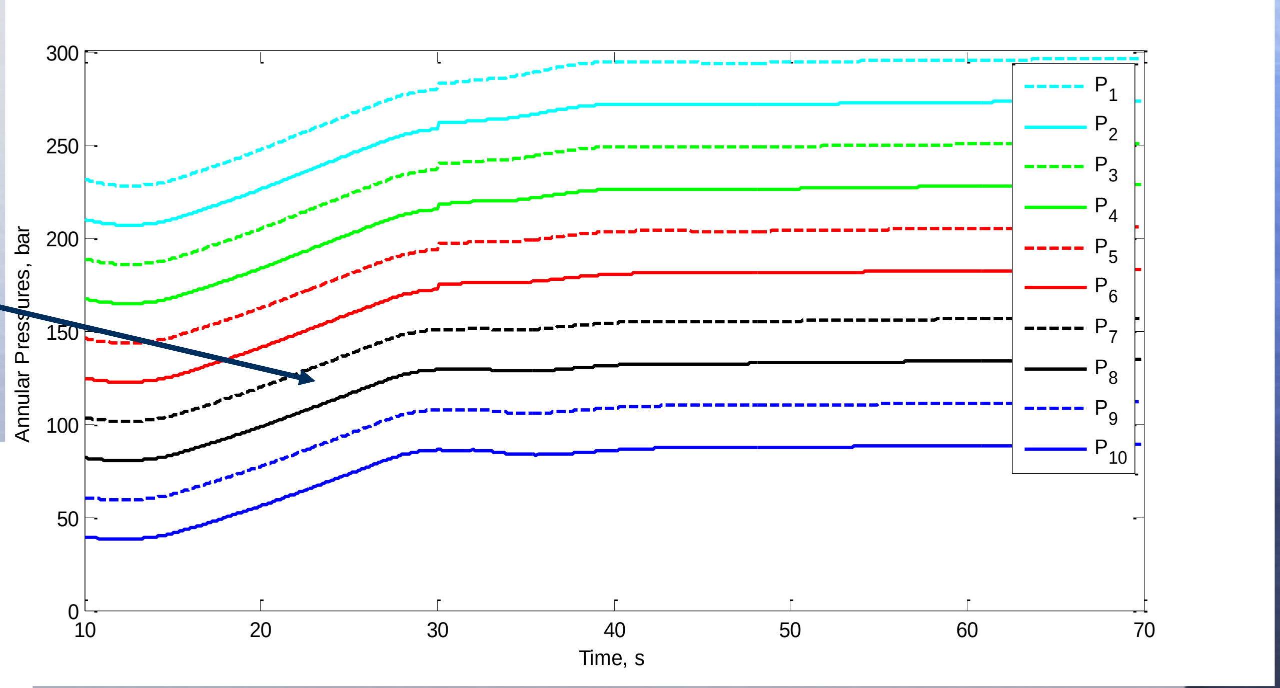
Cuttings Buildup Protection

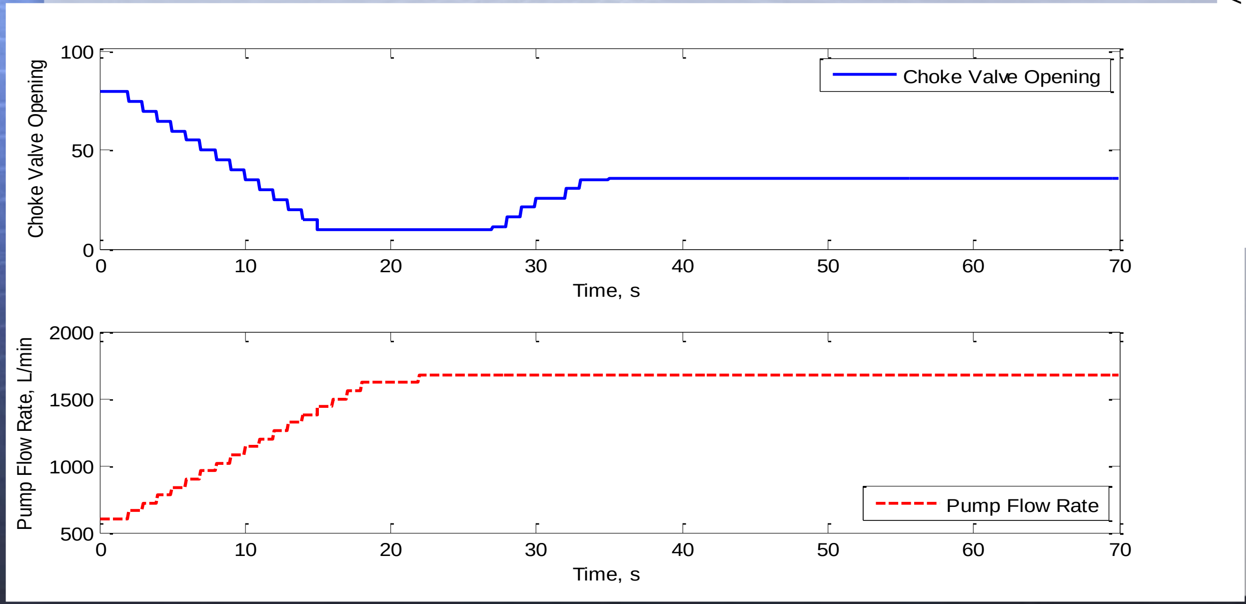


- Early detection of cuttings buildup can improve the operational strategy for cuttings removal.
- The higher density estimate from location 5 (middle point in the axial direction of the annulus) is an indication of cuttings buildup.

Cuttings Buildup Protection

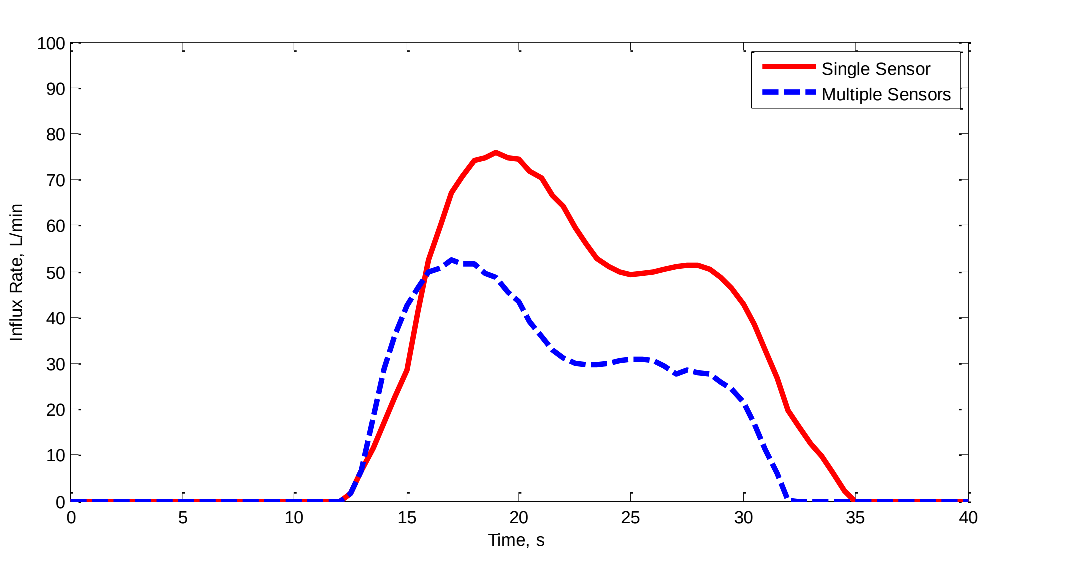
- Slight increase in pressure at location 5 relative to the other pressure sensors would be difficult for an operator to identify.





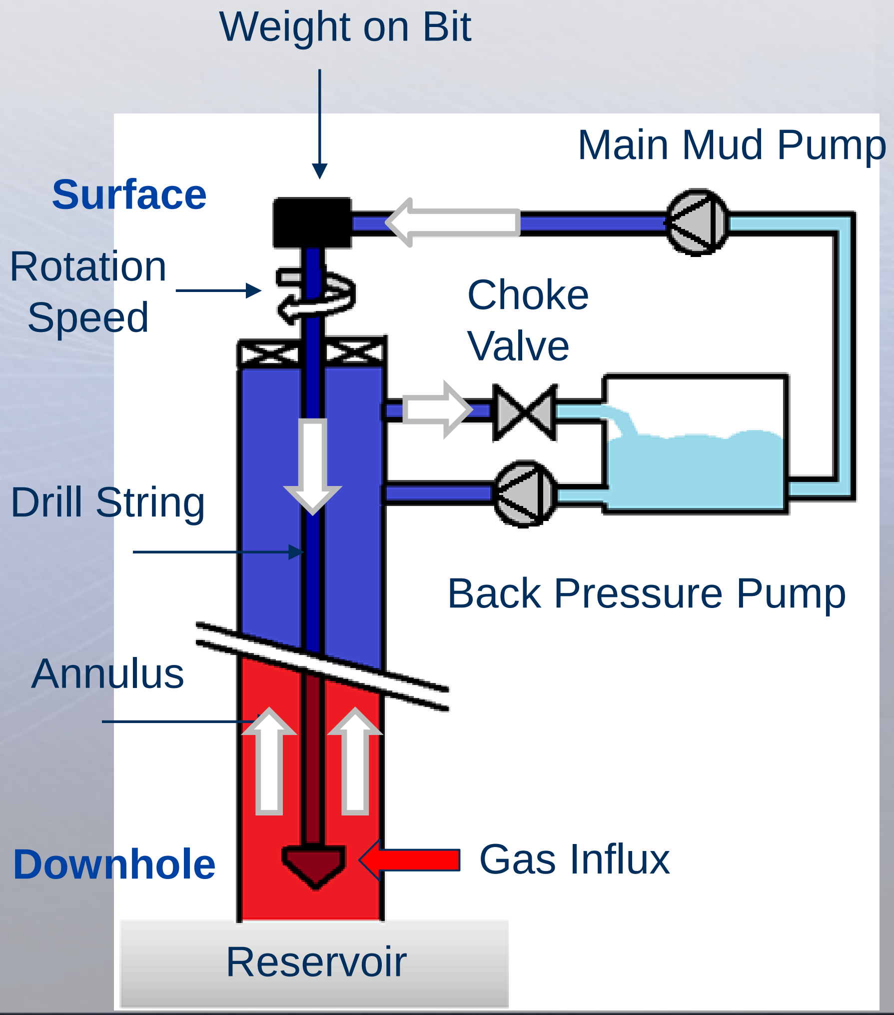
- The density estimates are fed to the predictive controller to update the underlying model used in the forward looking optimization

Distributed Pressure Measurements



- The pressure sensor closer to the kick location is able to sense the change earlier and with a higher degree of accuracy.
- The comprehensive controller manipulates the RPM, pump flow, and choke valve opening simultaneously to attenuate the kick.

Managed Pressure Drilling



Known variables:
- Surface measurements
- Downhole RPM, WOB
- Annulus pressure (mud pulse / wired pipe)

Unknown variables in annulus:
- Density (annulus)
- Friction Factor (annulus)
- Downhole drilling fluid and gas influx flow rate

Previous Work in MPD

Improve Economics

Two Controllers

Improve Safety

Optimization: Maximize ROP

RPM → System f(RPM,WOB,BHP) → ROP
WOB →

- Ignore change of WOB and RPM along drill string
- Ignore effect of downhole pressure dynamics
- Potential for ROP improvement

Automation: BHP Regulation

Z_{choke} → System $f(Z_{choke},q_{pump},\text{friction})$ → BHP
q_{pump} →

- Surface measurements (without WDP)
  - Delayed response to kick events
  - Estimation of fluid properties difficult
  - Reactive pressure control vs. proactive
- Most prior work with linear controllers
- Decreased and more variable ROP

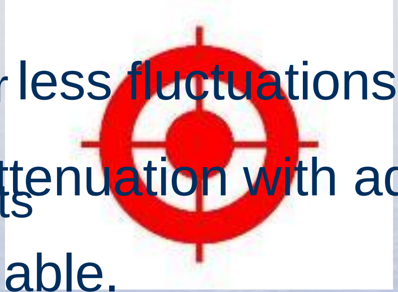
Is it possible to design a comprehensive controller which considers both tasks simultaneously?

Proposed Comprehensive Controller

Expected Advantages

- Higher ROP and less fluctuations in that.
- Improved Kick attenuation with adding extra manipulated variable.
- Earlier detection of cuttings loadings during drilling.
- Improved safety and reduced drilling cost.

Single Controller Considers Multivariate Effects



Comprehensive Controller: Maximize ROP + Regulate BHP

Z_{choke}

q_{pump}

RPM

WOB

System

BHP

ROP

Features of Comprehensive Controller

- Comprehensive controller which controls ROP and BHP simultaneously.
- Considers the interaction between drill string and hydraulics.
- Kick attenuation methodology based on the direct BHP measurements using wired pipe telemetry.
- Designing multivariate controller using multiple sensor measurement along annulus.

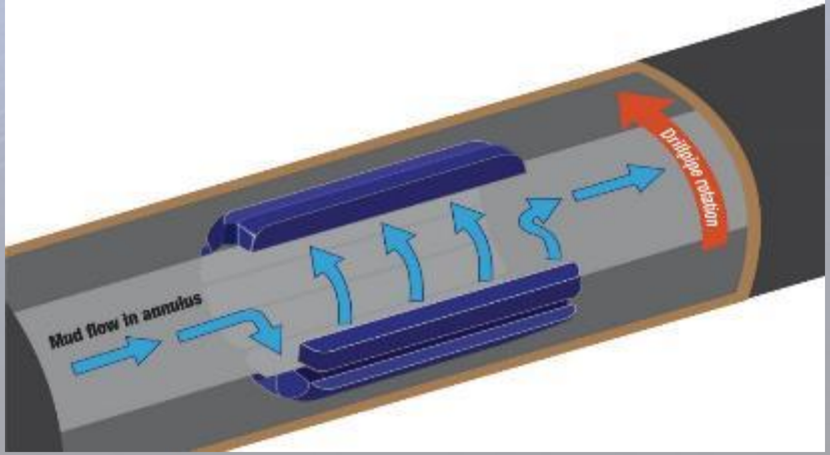
Model Components

Pressure Hydraulics

- Lower order model (Stames et. al)

Interaction Between Drill String and Hydraulics

- ROP also depends on the downhole pressure
  - ROP, Bourgoyne & Young Model
- Friction factor in the annulus depends both on axial and rotational flow of the mud



http://wwtinternational.com/index.php/torque_reduction

- Rotation Speed (RPM) effect on Friction Factor

$$f_a = a\, Re_{axial}^{b} + c\, Re_{angular}$$

Drill String Dynamics

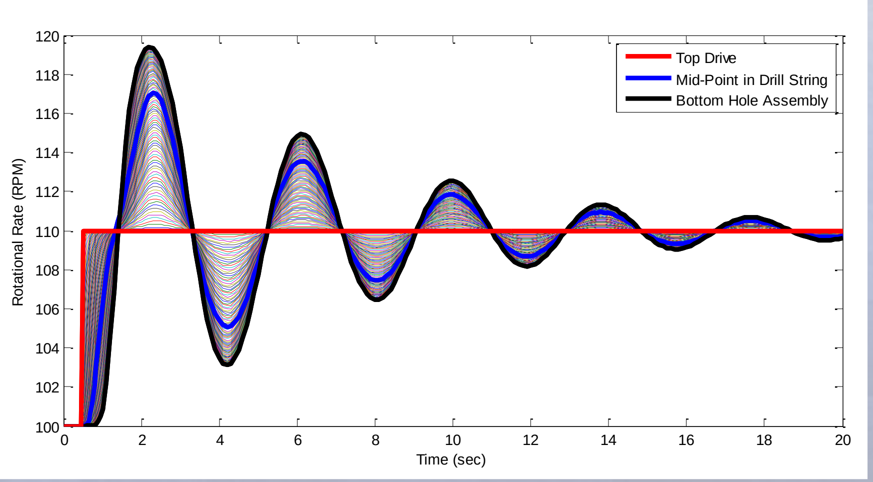
- Drill String Dynamics
  - Multiple mass-spring-damper pendulums in series
  - Johannessen, M.K. and T. Myrvold
- WOB Dynamics
  - First order plus dead time model
  - Surface WOB -> Downhole WOB

Model Components (Cont.)

- Drill String Dynamics
  - Multiple mass-spring-damper pendulums in series
  - Johannessen, M.K. and T. Myrvold

- WOB Dynamics
  - First order plus dead time model
    - Surface WOB -> Downhole WOB

- Rotation Speed (RPM) effect on Friction Factor
  - Fluid and cuttings rotational movement
  - Affect hydrostatic head downhole
  - Ozbayoglu et al. model



$$f_a = a\, Re_{axial}^{b} + c\, Re_{angular}$$

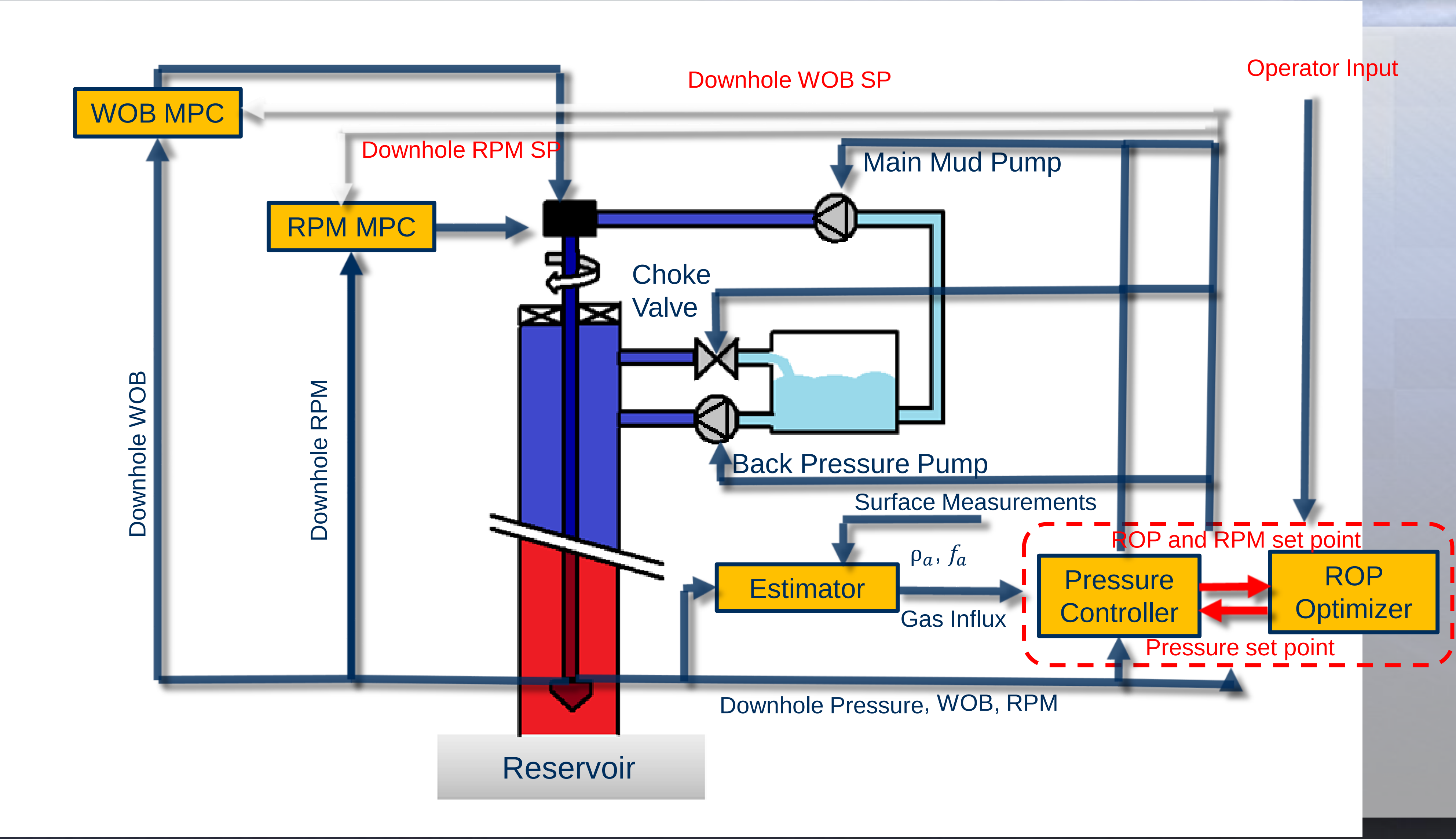
$$Re_a = \frac{757\, \rho\, v_a\, (D_o - D_i)}{\mu_a}$$

Velocity in Axial Direction

$$Re_\omega = \frac{2.025\, \rho\, RPM\, (D_o - D_i)\, D_i}{\mu_\omega}$$

Rotation Speed of Drill String

Control System Scheme



Kick Attenuation Mode

Normal Drilling Operation

$P_{bit} > Safety\ Margin + P_{sp}$ and $q_{influx} > 0$

Switch the controlled variable from downhole pressure into choke valve pressure and set the set point as

$$P_C^{SP} = P_C^{before\ kick} + k_p E + k_I \int E + k_d \frac{dE}{dt}$$

$$E = P_{bottom}^{current} - P_{bottom}^{sp}$$

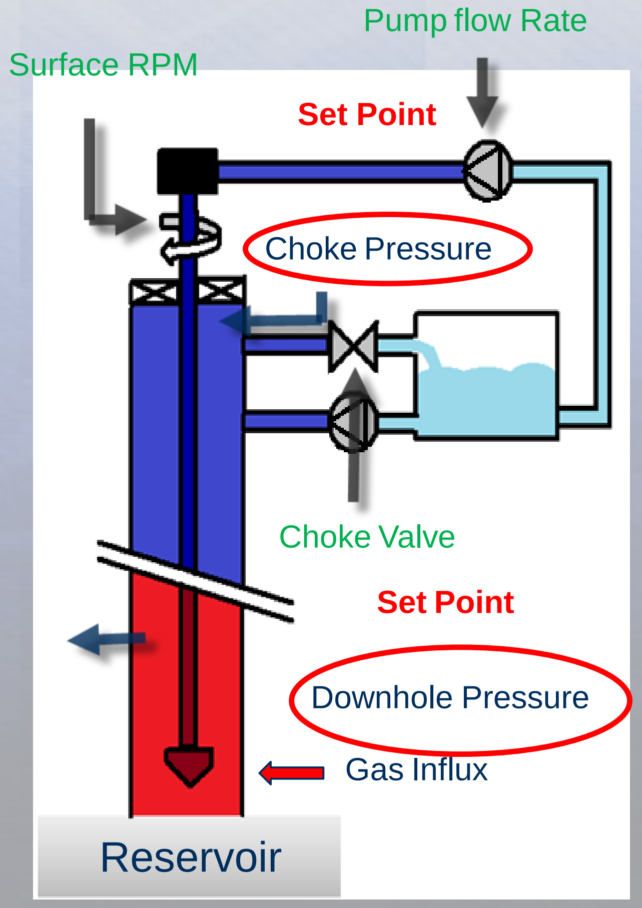
Change choke valve opening, surface RPM and pump flow rate

Hold until $q_{influx} <$ specified limit

Switch the controlled variable from choke valve pressure to downhole pressure

Calculate the new reservoir pore pressure (P_{res})

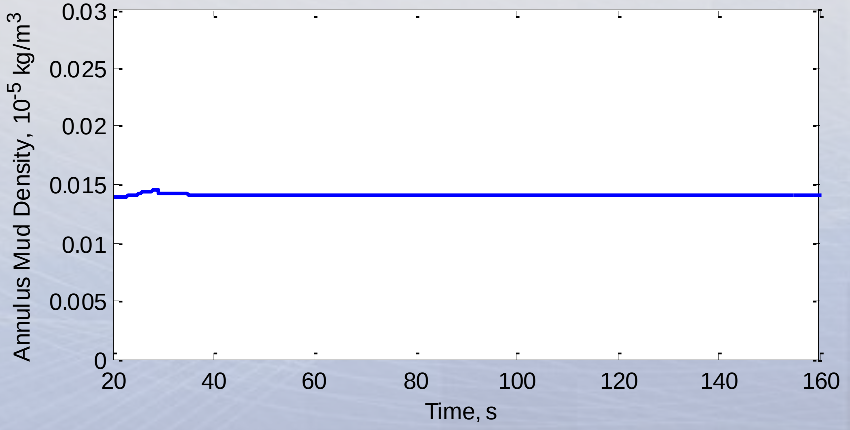
- **Kick attenuation has higher priority than achieving higher ROP**

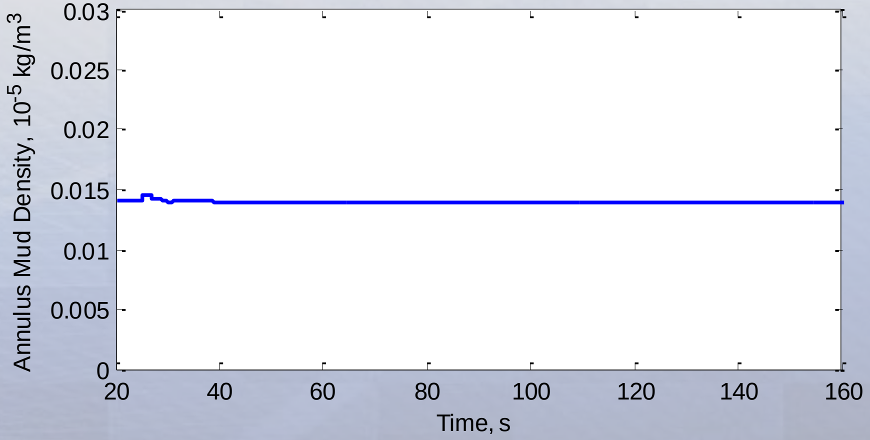


Less Sensitive to Bad Data

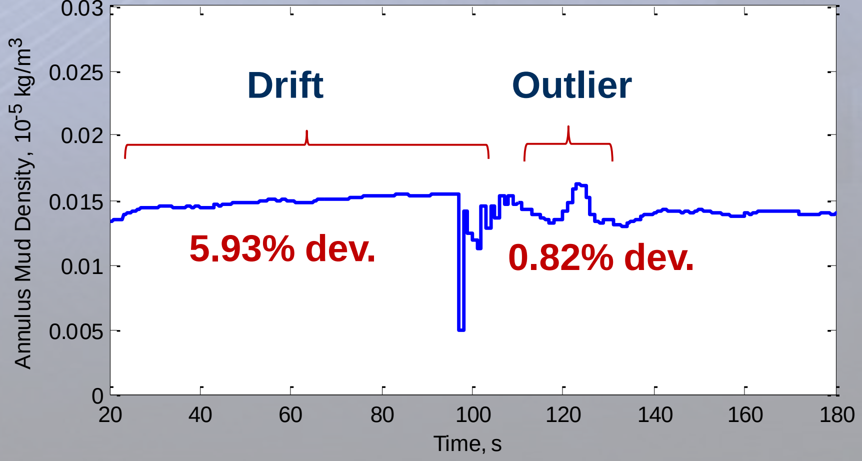
Squared Error | **ℓ1-norm**

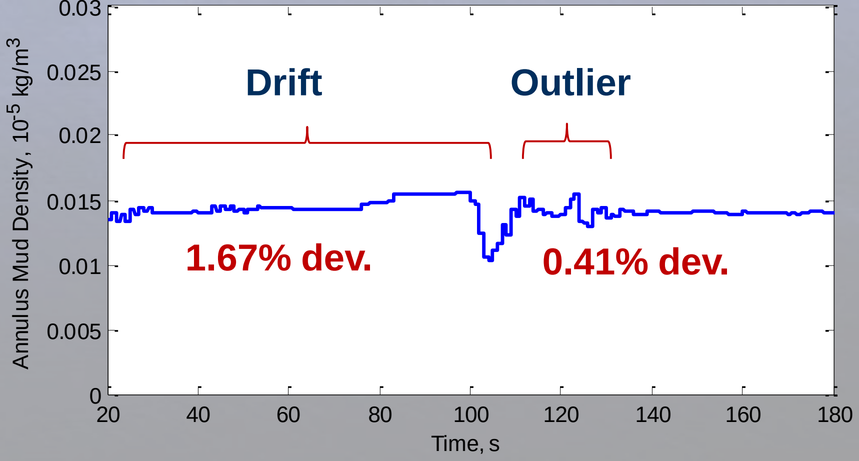
Clean Data





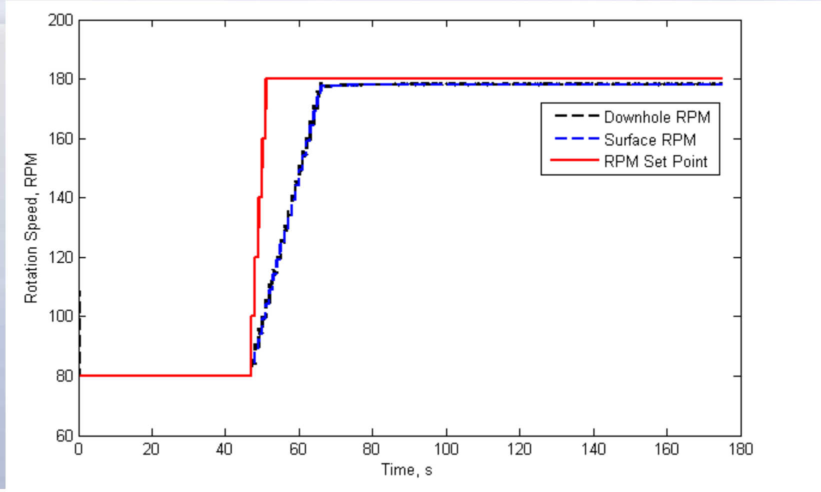
Corrupted Data

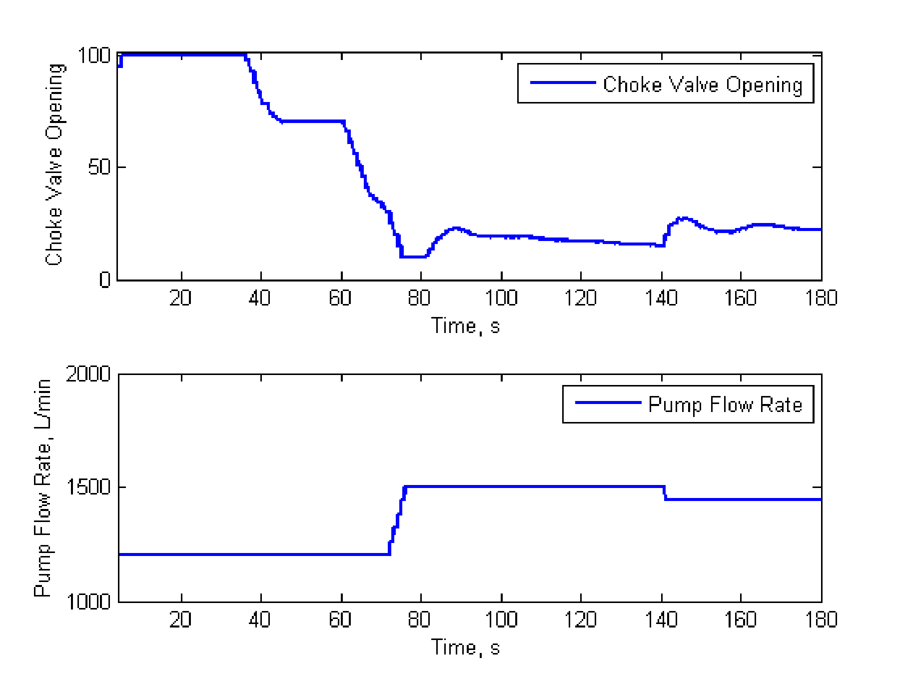


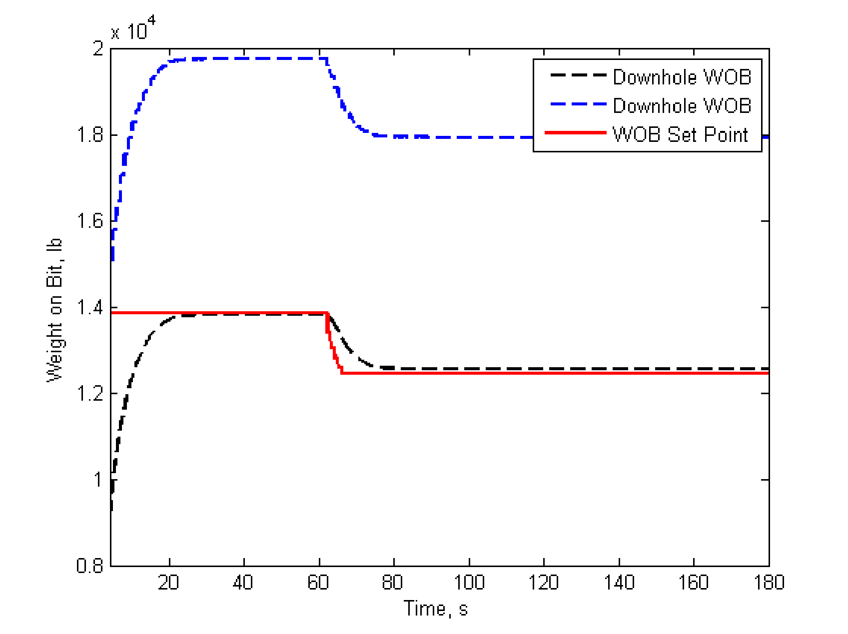


Controller Results

- Drilling continues with consistent ROP during kick.
- Avoids cutting build up issues due to ROP fluctuations.







Publications

Accepted Journal Articles

- Asgharzadeh Shishavan, R., Hubbell, C., Perez, H.D., Hedengren, J.D., and Pixton, D.S., Combined Rate of Penetration and Pressure Regulation for Drilling Optimization Using High Speed Telemetry, SPE Drilling and Completions Journal, accepted for publication / in press.
- Hedengren, J. D. and Asgharzadeh Shishavan, R., Powell, K.M., and Edgar, T.F., Nonlinear Modeling, Estimation and Predictive Control in APMonitor, Computers and Chemical Engineering, Volume 70, pg. 133–148, 2014.
- Asgharzadeh Shishavan, R, Perez, H., Hedengren, J., Brigham Young University; Pixton, D.S., NOV IntelliServ; Pink, A.P., National Oilwell Varco, Multivariate Control for Managed Pressure Drilling Systems Using High Speed Telemetry, Submitted to SPE Journal, under review.

Submitted Journal Articles

- Reza Asgharzadeh Shishavan, David S. Pixton, Ammon N. Eaton, Junho Park, Hector D. Perez, and John D. Hedengren and Andrew Craig, Addressing UBO and MPD Challenges with Wired Drillpipe, Submitted to SPE Journal, under review.

Publications Cont.

Peer Review Conference Papers

- Asgharzadeh Shishavan, R., Perez, H., and Hedengren, J.D., Multivariate nonlinear model predictive controller for managed drilling processes, AIChE Annual Meeting, Atlanta, GA, Nov 2014.
- Asgharzadeh Shishavan, R., Hubbell, C., Perez, H.D., Hedengren, J.D., Pixton, D.S., and Pink, A.P., Multivariate Control for Managed Pressure Drilling Systems Using High Speed Telemetry, SPE Annual Technical Conference and Exhibition (ATCE), Amsterdam, The Netherlands: 27-29 Oct 2014.
- Asgharzadeh Shishavan, R., Hubbell, C., Perez, H.D., Hedengren, J.D., and Pixton, D.S., Combined Rate of Penetration and Pressure Regulation for Drilling Optimization Using High Speed Telemetry, SPE Deepwater Drilling and Completions Conference, Galveston, TX: 10-11 Sept 2014.
- Asgharzadeh Shishavan, R., Brower, D.V., Hedengren, J.D., Brower, A.D., New Advances in Post-Installed Subsea Monitoring Systems for Structural and Flow Assurance Evaluation, ASME 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE2014/24300, San Francisco, CA, June 2014.
- Brower, D.V., Brower, A.D., Hedengren, J.D., Asgharzadeh Shishavan, R., A Post-Installed Subsea Monitoring System for Structural and Flow Assurance Evaluation, Offshore Technology Conference, OTC 25368, Houston, TX, May 2014.
- Pixton, D., Asgharzadeh Shishavan, R., Hedengren, J.D., and Craig, A., Addressing UBO and MPD Challenges with Wired Drillpipe, SPE/IADC MPD & UBO Conference & Exhibition, Madrid, Spain: 8 - 9 Apr 2014.
- Brower, D., Hedengren, J.D., Asgharzadeh Shishavan, R., and Brower, A., Advanced Deepwater Monitoring System, ASME 32st International Conference on Ocean, Offshore and Arctic Engineering, OMAE2013/10920, Nantes, France, June 2013, ISBN: 978-0-7918-5531-7.

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Publications Cont.

Conference Proceedings

- Asgharzadeh Shishavan, R., Memmott, J., Hedengren, J.D, and Pixton, D., Pressure Regulation and Kick Attenuation with Wired Pipe Technology in Managed Pressure Drilling. AIChE Spring Meeting, New Orleans, LA, April 2014. Asgharzadeh Shishavan, R. and Hedengren, J.D.,
- Improved Estimator Insensitivity to Outliers, Measurement Drift, and Noise, AIChE Spring Meeting, New Orleans, LA, April 2014. Brower, D., Brower, A., Memmott, J.A.,
- Hedengren, J.D., Mojica, J.L., Asgharzadeh Shishavan, R., Safdarnejad, S.M., Recent Advances in the Application of MIDAE Systems, AIChE National Meeting, San Francisco, CA, Nov 2013.