Real-Time Control and Online Parameter Estimation for Drill String Dynamics Modeling

MATLAB Energy Conference 2021

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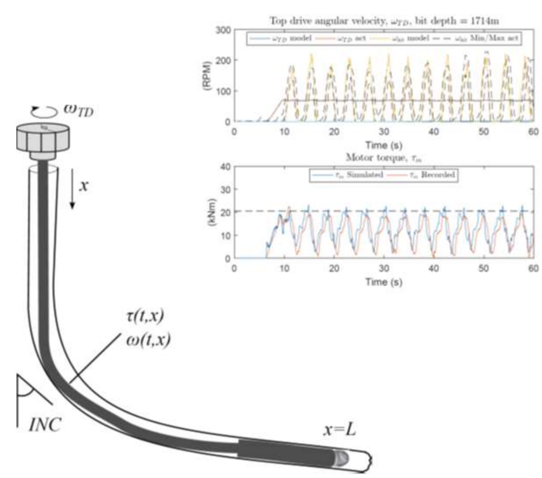
Agenda

- Introduction & Motivation
- Drillstring & Friction Model
- Field Validation
- Stick-slip Mitigation Systems
- Benchmarking Systems
- Simulation Study
- Conclusions & Further Work



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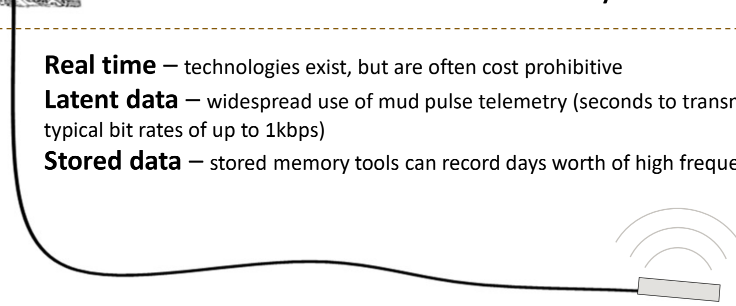
Introduction

Surface Data Collection

RPM, Torque, Hookload, Pumprate, Pressure, Flow, etc

Real time – typically recorded at 1-10Hz
Often Asynchronous

Real time – technologies exist, but are often cost prohibitive
Latent data – widespread use of mud pulse telemetry (seconds to transmit data with typical bit rates of up to 1kbps)
Stored data – stored memory tools can record days worth of high frequency data



Downhole Data Collection

RPM, Torque, Weight-on-bit, Pressure, Vibration, etc

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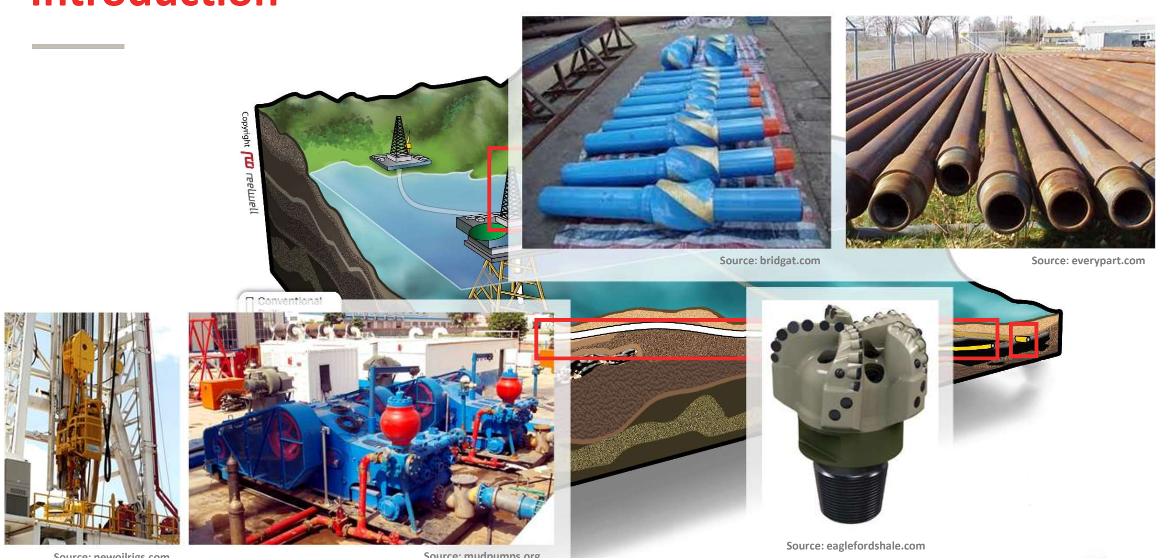
Introduction



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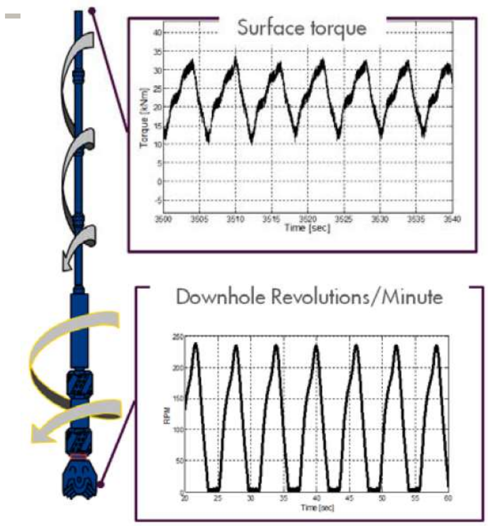
What is Stick-Slip?



- Cyclic stopping (sticking) and releasing (slipping) of the bit and bottom hole assembly during drilling operations
- 3-10 second period (dependent on drillstring length)
- Visible at surface as a fluctuation in torque

Runia et al., 2013

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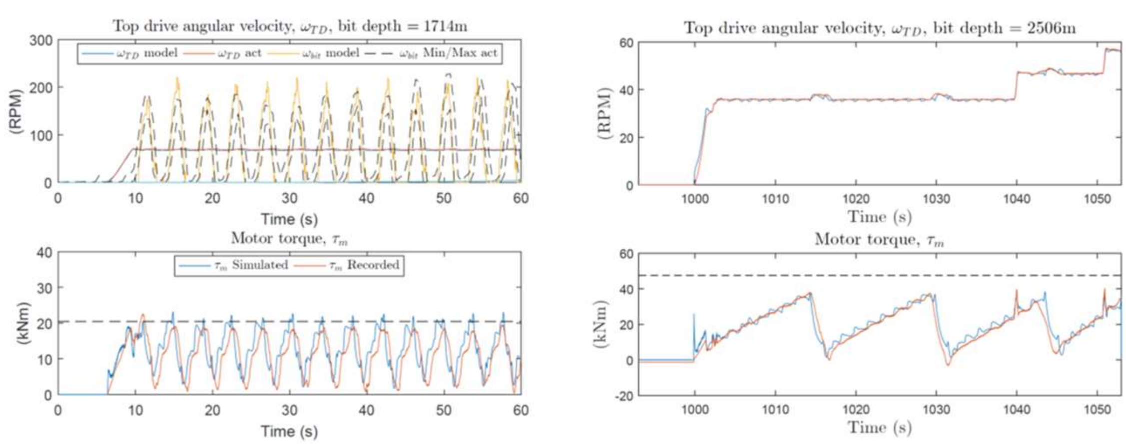
Motivation



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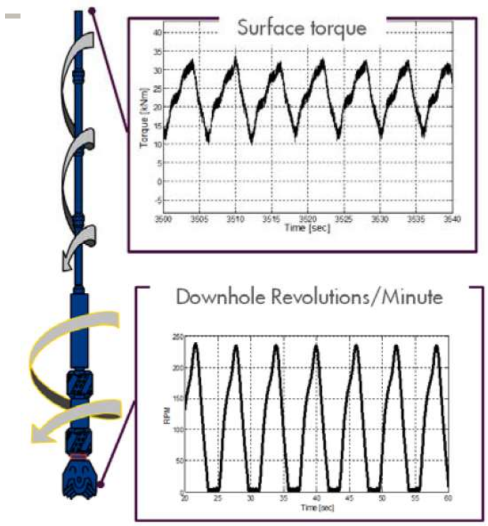
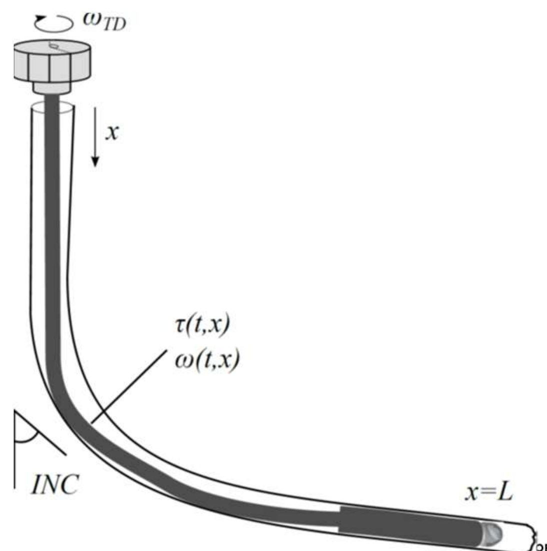
Drillstring Model





Runia et al., 2013

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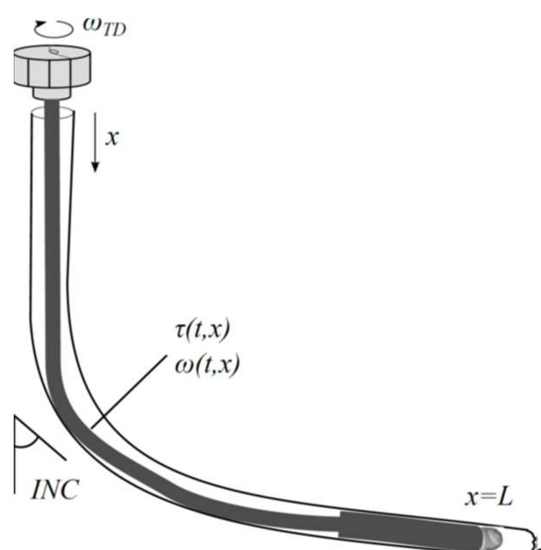
Drillstring Model

- Top drive at surface with polar moment of inertia I_{TD} and stiff PI controller
- Stick-slip can be caused by
  - Bit-rock interaction
  - **Friction along drillstring**



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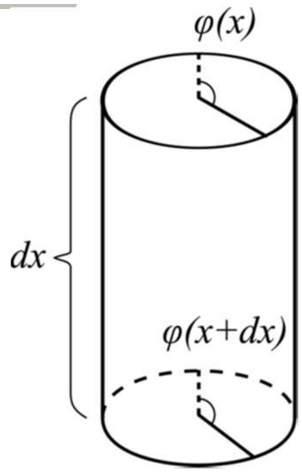
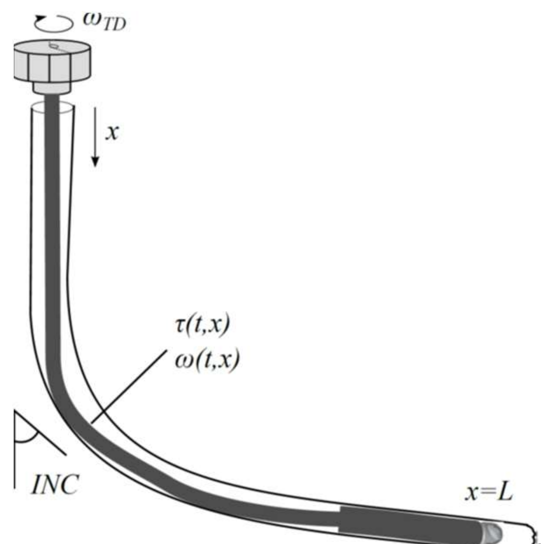
Drillstring Model





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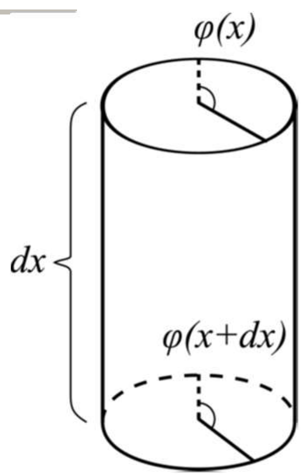
Drillstring Model



- Dynamics governed by the torsional wave equation

$$\frac{\partial \tau(t,x)}{\partial t} + JG\frac{\partial \omega(t,x)}{\partial x} = 0$$
$$J\rho\frac{\partial \omega(t,x)}{\partial t} + \frac{\partial \tau(t,x)}{\partial x} = S(\omega, x)$$

- where

τ – torque
ω – angular velocity
ρ – density

J – polar moment of inertia
G – shear modulus

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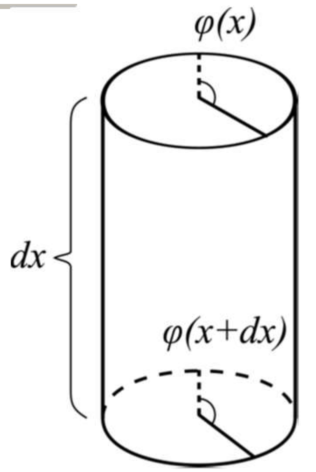
Drillstring Model



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$$J\rho\frac{\partial \omega(t,x)}{\partial t} + \frac{\partial \tau(t,x)}{\partial x} = S(\omega,x)$$

- Source term is modeled by Coulomb Friction

$$S(\omega,x) = -k_t\rho J\omega(t,x) - \mathcal{F}(\omega,x)$$

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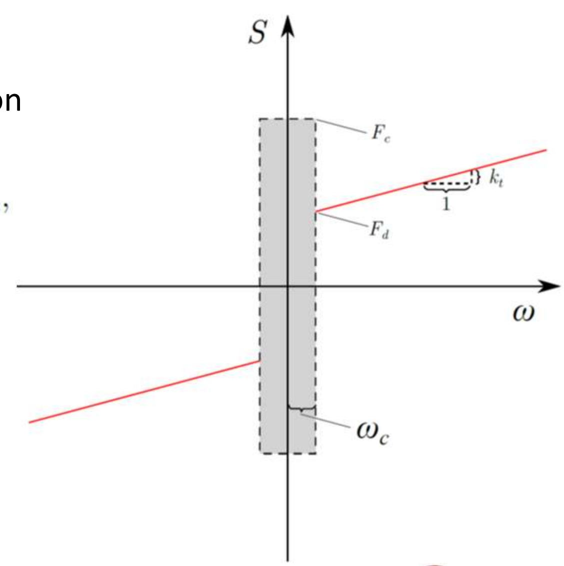
Coulomb Friction

- Coulomb friction is modeled as an inclusion

$$\begin{cases} \mathcal{F}(\omega,x) = F_d(x), & \omega > \omega_c, \\ \mathcal{F}(\omega,x) \in [-F_c(x), F_c(x)], & |\omega| < \omega_c, \\ \mathcal{F}(\omega,x) = -F_d(x), & \omega < \omega_c, \end{cases}$$

- with the parameters:
  - F_c, maximum Coulomb torque, or alternatively, μ, coefficient of friction
  - ω_c, the transition angular velocity
  - k_t, the viscous friction coefficient



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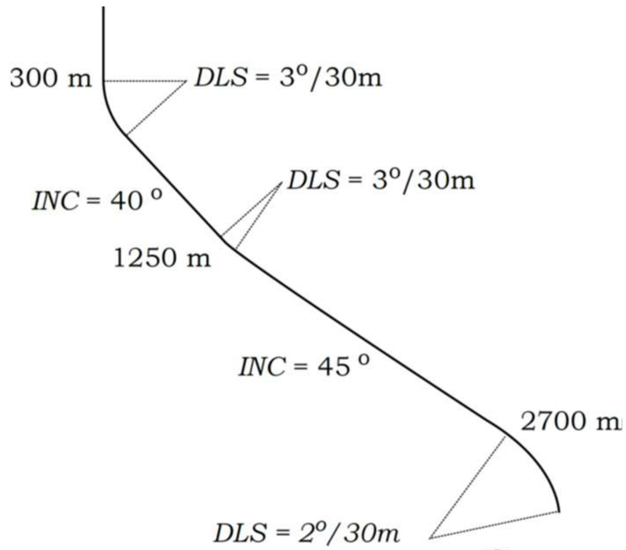
Field Example

- **Inertia dominated oscillations**

- 200 Hz surface data
- 10s min/max/mean downhole data



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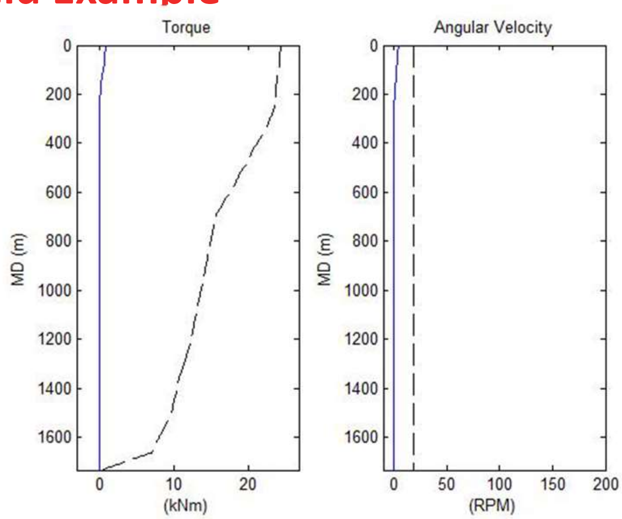
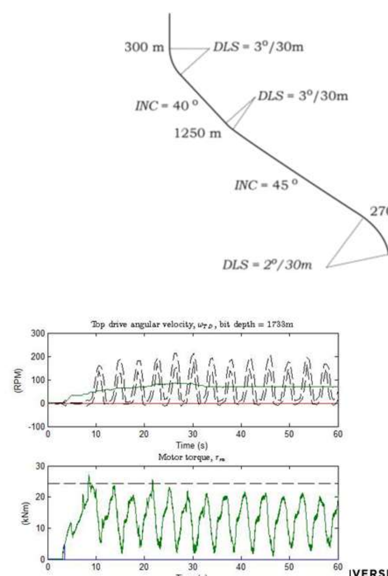
Field Example





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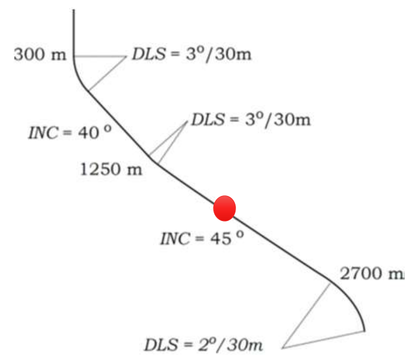
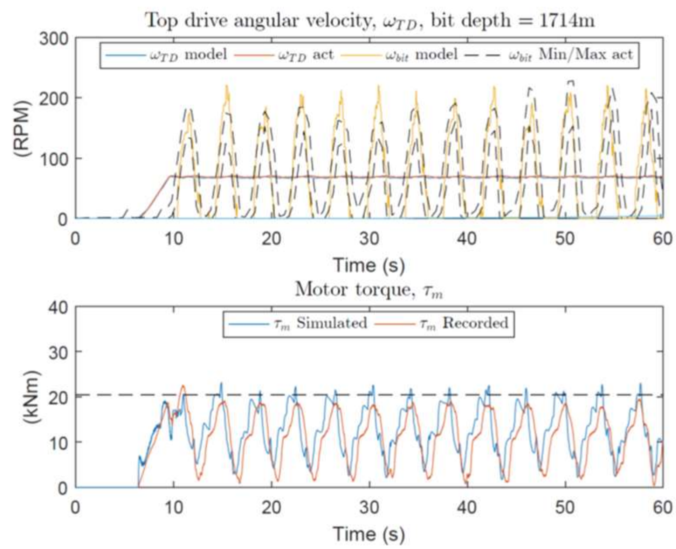
Field Example





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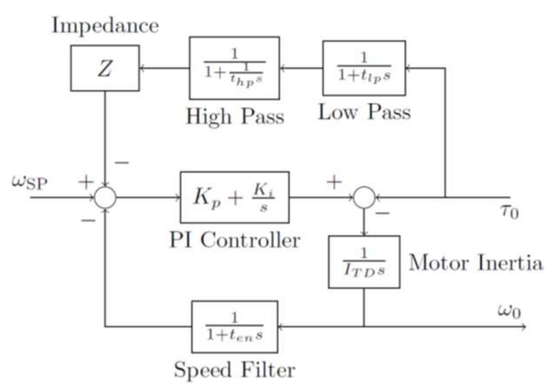
Stick-slip Mitigation Control

- Top Drive Speed Control:
  1. Stiff speed control
  2. Tuned PI control
     - SoftTorque / SoftSpeed
  3. Impedance Matching Control
     - ZTorque



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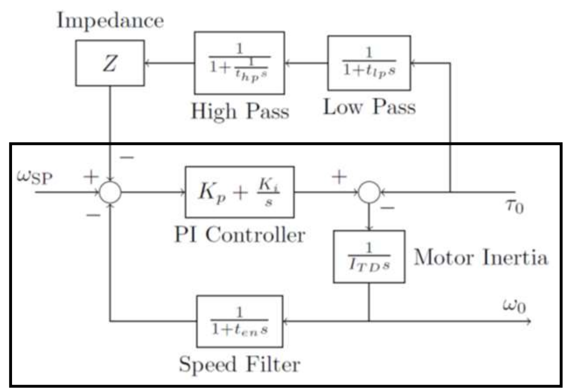
Stick-slip Mitigation Control

- Top Drive Speed Control:
  - **Stiff speed control**
    - $K_p = 100\zeta_p$
    - $K_i = 5I_{TD}$
    - where,

      $\zeta_p = J_p\sqrt{G_p\rho}$ is pipe impedance, and

      I_{TD} is the top drive inertia



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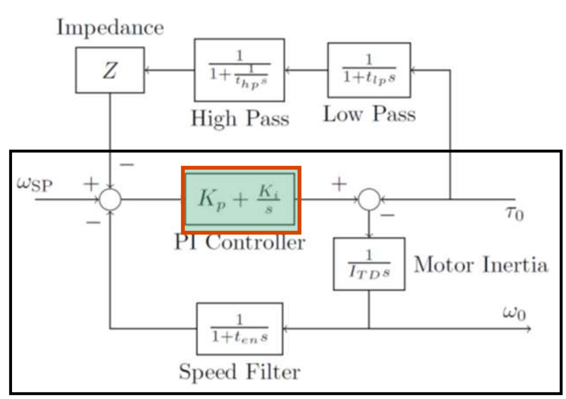
Stick-slip Mitigation Control

- Top Drive Speed Control:
  - **Tuned PI control**
    - Marketed as SoftTorque / SoftSpeed
    - $K_p = 4\zeta_p$
    - $K_i = (2\pi f_c)^2 I_{TD}^2$
    - where,

      f_c is the frequency (in Hz) of minimal reflectivity



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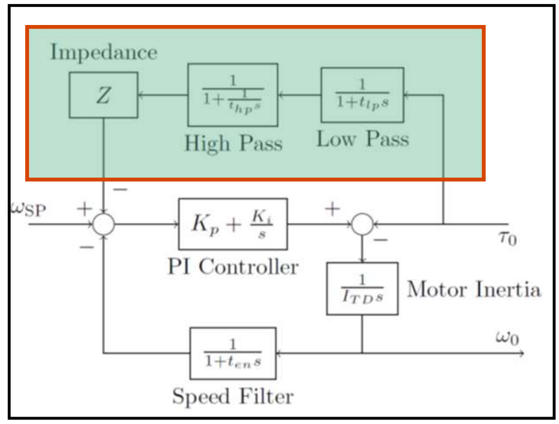
Stick-slip Mitigation Control

- Top Drive Speed Control:
  - **Impedance Matching Control**
    - Marketed as Ztorque
    - Desired top drive speed to match pipe impedance given by
      - $\omega_o(t) = \frac{1}{\zeta_p} \cdot \tau_o(t)$



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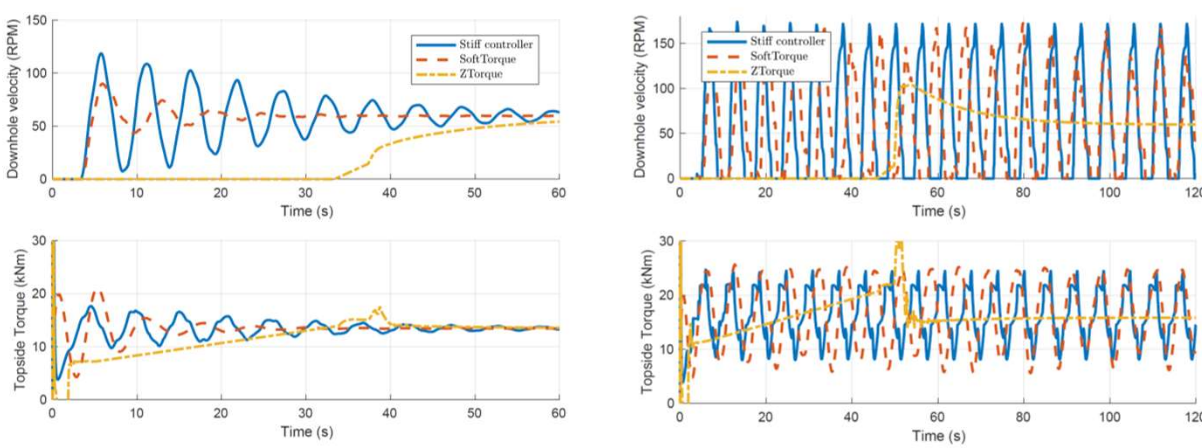
Stick-slip Mitigation Control



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Evaluating Performance

- Concept of *reflectivity*

$$R(\omega) = \left| \frac{\bar{C}(s) - \zeta_p}{\bar{C}(s) + \zeta_p} \right|$$

where

$$\bar{C}(s) = \frac{\tau_o(s)}{\omega_o(s)} = C(s) + I_{td}s = \frac{\tau_m(s)}{\omega_o(s)} + I_{td}s$$

$$\zeta_p = J_p\sqrt{G_p\rho}$$

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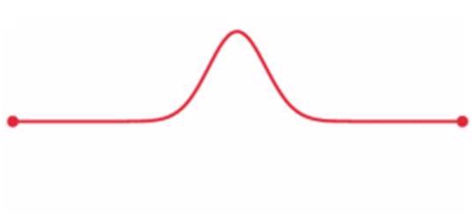
Top Drive Reflectivity

- **Traditional stiff speed controller**
  - Reflects torsional waves back to the bit



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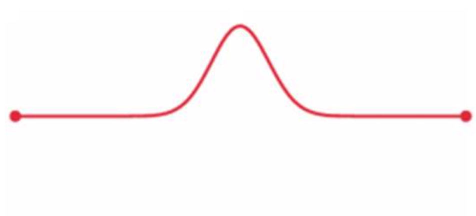
Top Drive Reflectivity

- **Traditional stiff speed controller**
  - Reflects torsional waves back to the bit
- **Ideal zero reflection boundary**
  - Transmits all wave energy into space and does not reflect it downhole



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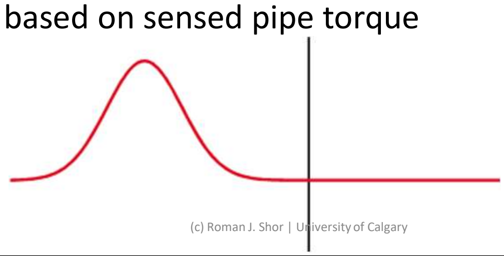
Impedance Matching Control

- **Impedance Matching**
  - The drillstring has a **characteristic impedance**, which can be calculated

$$\zeta_p = J_p\sqrt{\rho G} = \frac{\omega_0}{\tau_0}$$

  - A control system may then **match** the drillpipe impedance by changing rpm based on sensed pipe torque



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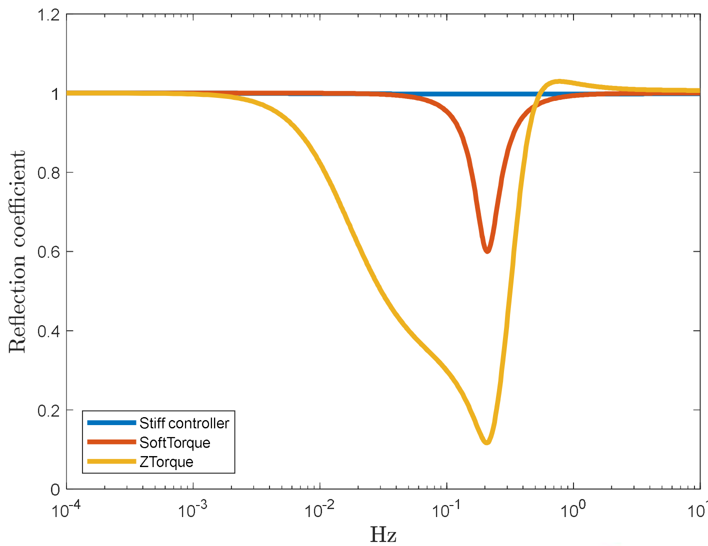
Evaluating Effectivity

- **Stiff speed**: reflectivity of 1 at all frequencies
- **SoftTorque:** reflectivity reduced at tuning frequency
- **Ztorque:** improved range of reduced reflectivity.

  Limited by:
  - Tracking performance (high pass filter).
  - Instrumentation constraints (low pass filters and delays).



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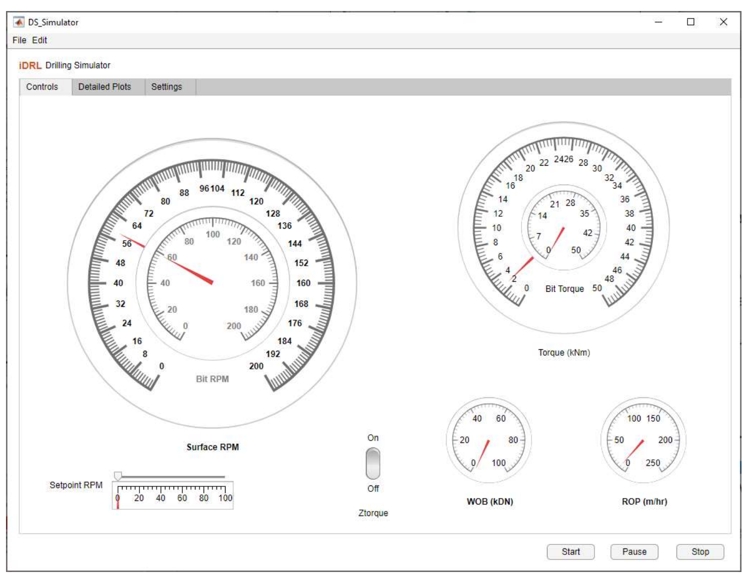
Data Evaluation



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Data Evaluation

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Conclusions

- Basic torsional model able to replicate different modes of stick slip caused by side forces
  - Ratio between static and kinematic friction key parameter
- Industry controllers tested using model:
  - SoftTorque/SoftSpeed reduces stick-slip tendency but may increase severity when the ratio between static and kinematic friction is below 0.8
  - Ztorque with torque measurement removes stick slip
    (but might be limited by delays / latency / filtering in practice)
- Reflectivity coefficient good predictor of performance.

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Acknowledgements

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- Schulich School of Engineering at the **University of Calgary**

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