Extremum seeking for real-time optimal drilling control

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How to optimize drilling parameters?

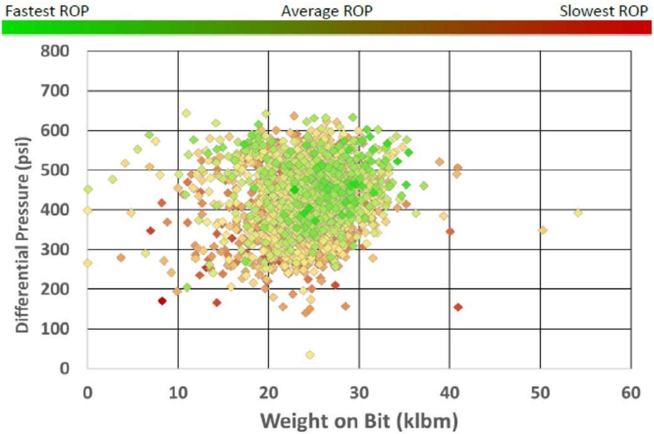
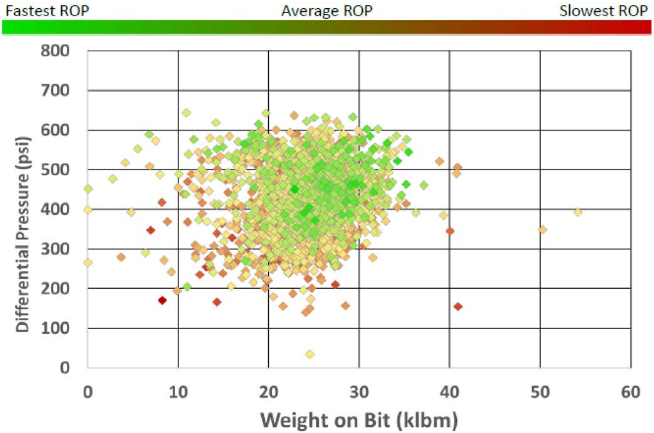


Figure: Net ROP correlation for 36 wells (Maidla et al. (2018)).

How to optimize drilling parameters?

- Optimal drilling parameters are dependent on changing conditions.



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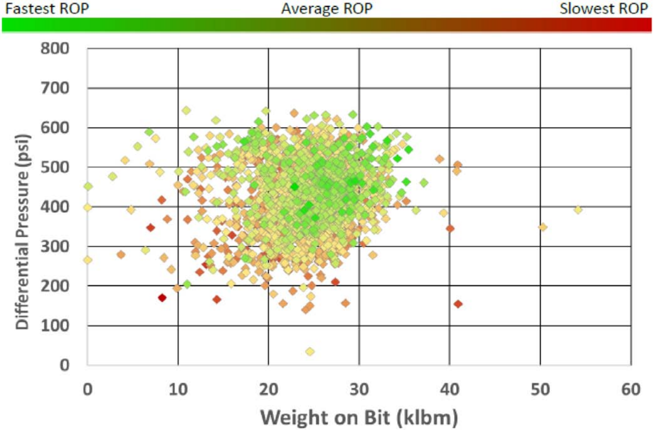
How to optimize drilling parameters?

- Optimal drilling parameters are dependent on changing conditions.
- Varies between wells and from stand to stand.



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ROP and bit foundering

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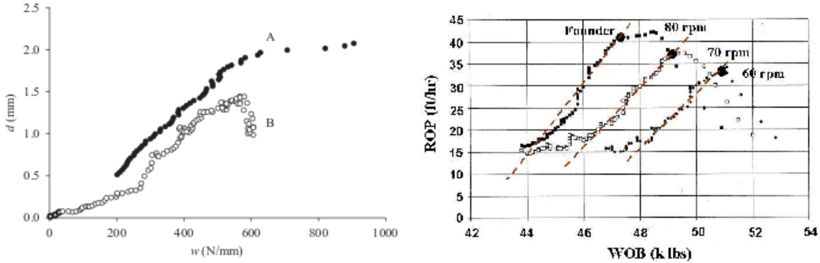
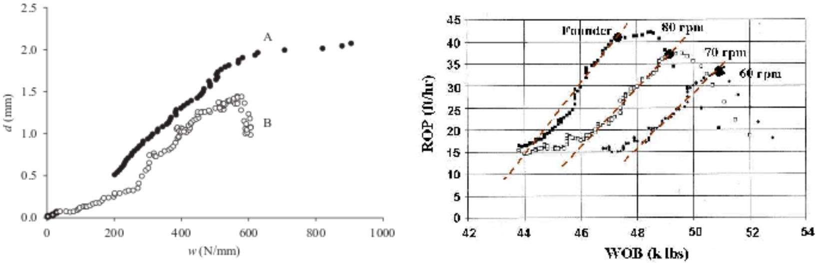


Figure: Bit foundering in laboratory tests **(left)** due to Detournay et al. (2008) and as seen in the field **(right)** due to Dupriest and Koederitz (2005).

ROP and bit foundering

- Drilling becomes inefficient beyond certain *WOB* (bit foundering).
- Founder point dependent on *cutter sharpness*, *rock properties*, *bit cleaning* etc.



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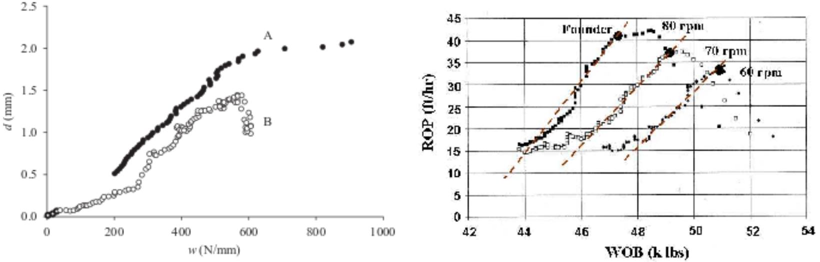
ROP and bit foundering

- Drilling becomes inefficient beyond certain *WOB* (bit foundering).
- Founder point dependent on *cutter sharpness*, *rock properties*, *bit cleaning* etc.
- Optimal *WOB* constantly changing.



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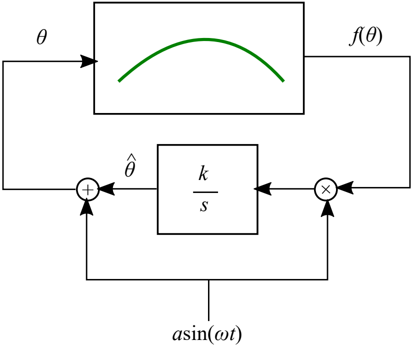
1. Optimal drilling parameters cannot be found solely from data-analysis and modeling ahead of time.
2. It *must* take the observered conditions of the current operation into account and adapt accordingly.

Proposed approach: Extremum seeking control

Arbitrary unknown quadratic function



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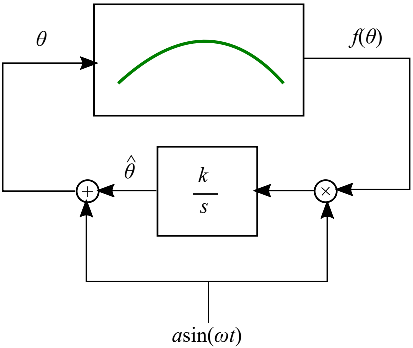

1. Add periodic perturbance to input

Proposed approach: Extremum seeking control

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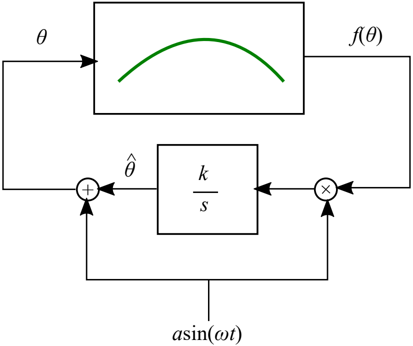

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2. Integrating the product of perturbation and output.

Proposed approach: Extremum seeking control

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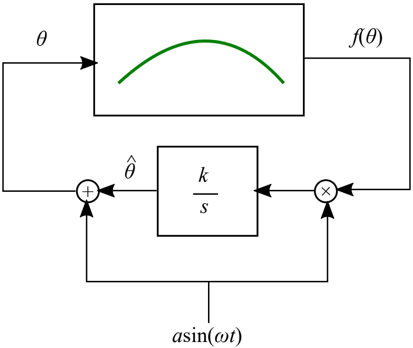

1. Add periodic perturbance to input
2. Integrating the product of perturbation and output.
3. In phase -> Increase, out of phase -> Decrease.

Proposed approach: Extremum seeking control

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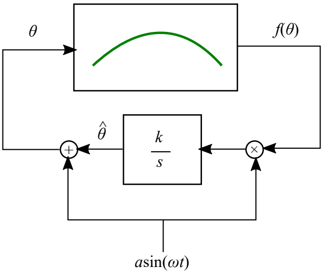
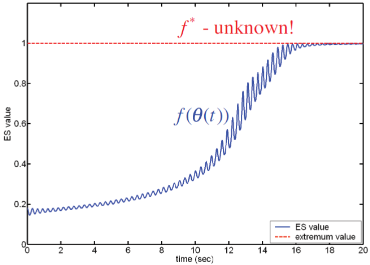
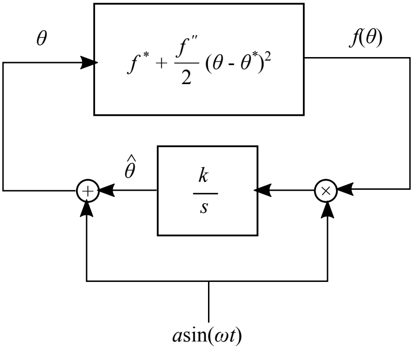




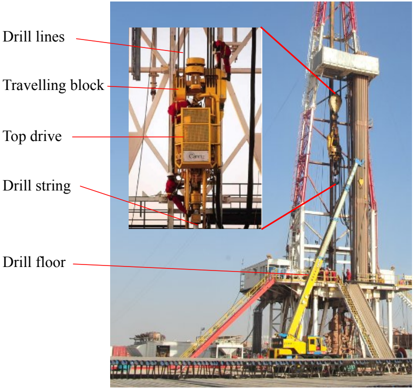
Arbitrary unknown quadratic function (Krstić and Wang, 2000)



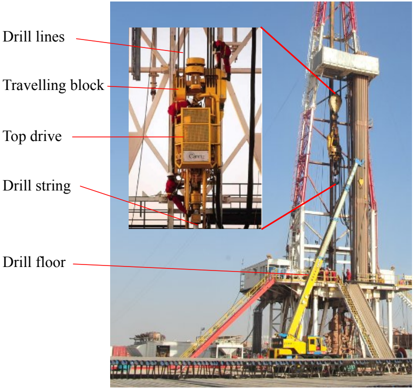
$$\tilde{\theta} = \hat{\theta} - \theta^* \tag{1}$$

$$\frac{\mathrm{d}\tilde{\theta}}{\mathrm{d}t} = ka\sin(\omega t)\left[f^* + \frac{f''}{2}\left(\tilde{\theta} + a\sin(\omega t)\right)^2\right] \tag{2}$$

Weight on bit control in drilling

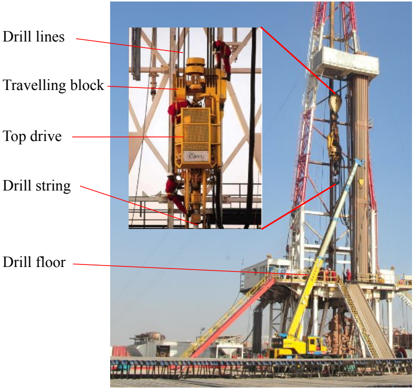


Weight on bit control in drilling



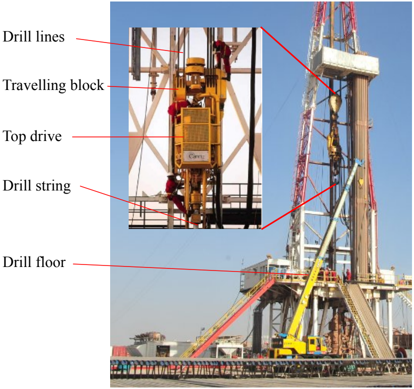
1. Top drive suspended by travelling block

Weight on bit control in drilling



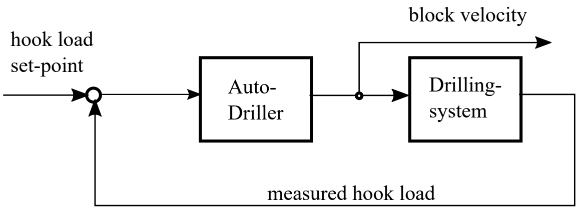
1. Top drive suspended by travelling block
2. Travelling block moved up and down by spooling drill lines

Weight on bit control in drilling

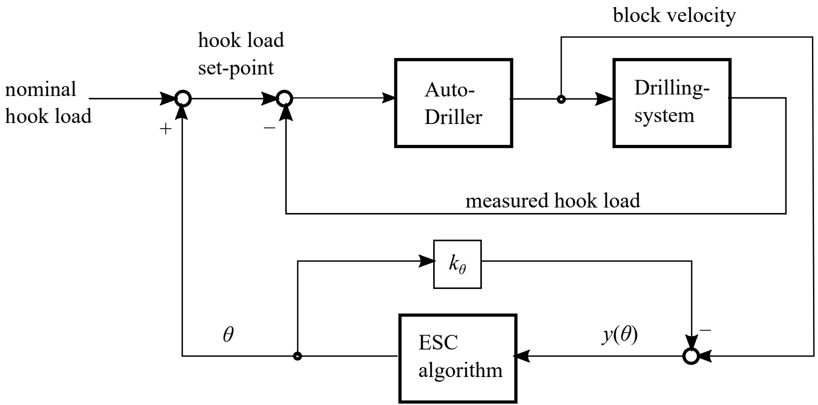


1. Top drive suspended by travelling block
2. Travelling block moved up and down by spooling drill lines
3. Hanging weight of drilling system measured as force at deadline (*hook load*)

Block diagrm

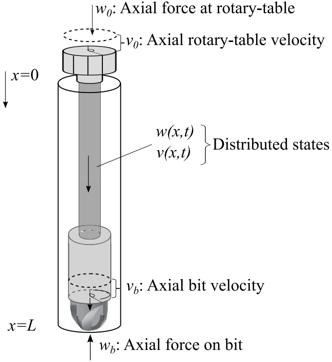


ESC scheme



block velocity
hook load
set-point
nominal
hook load
Auto-
Driller
Drilling-
system
+
−
measured hook load
k_θ
θ
ESC
algorithm
$y(\theta)$
−

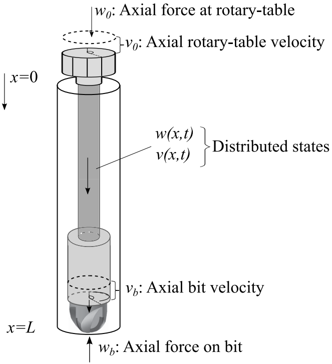
Simulation model



Topside boundary: Block velocity

$$v(t, x = 0) = v_0(t)$$

Simulation model



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Distributed dynamics

$$\frac{\partial w(t,x)}{\partial t} + AE\frac{\partial v(t,x)}{\partial x} = 0$$
$$\frac{\partial v(t,x)}{\partial t} + \frac{1}{A\rho}\frac{\partial w(t,x)}{\partial x} = F + G$$

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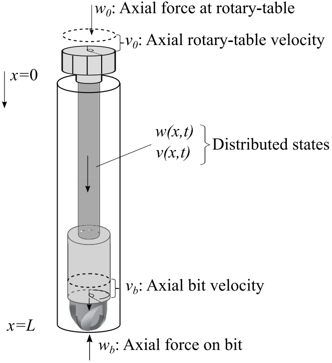

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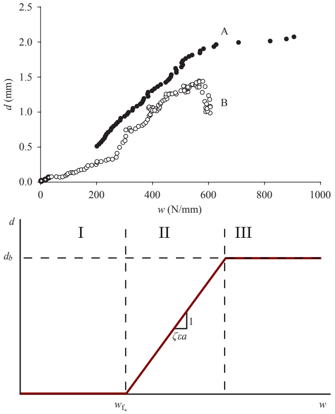
Bottom boundary: ROP

$$M_b\dot{v}_b = w_b(v_b, w_L) - w_L + \frac{\bar{\rho}}{\rho}M_b g,$$

Bit-rock interaction

Approximation of weight on bit – ROP relation:



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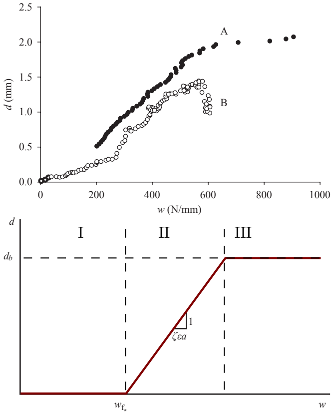

- Assume constant rotation ω_{bit}:

$$d(t) = \frac{v_b(t)}{\omega_{\text{bit}}} \tag{3}$$

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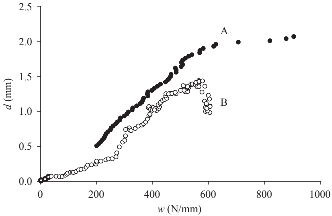

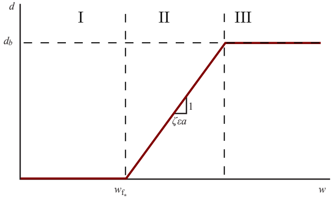

- Assume constant rotation ω_{bit}:

$$d(t) = \frac{v_b(t)}{\omega_{\text{bit}}} \tag{3}$$

- Weight on bit $w_b(d)$:

$$\begin{cases} w_b \in [0, w_{f*}], & d = 0 \\ w_b = w_{f*} + K_a d, & d_b > d \geq 0 \\ w_b \in [w_{f*} + K_a d_b, \infty], & d \geq d_b \end{cases}$$

Auto-driller (Boyadjieff et al., 2003)

- Control hook-load to w_0^{sp} by PI feedback:

$$v_0(t) = K_p(w_0(t) - w_0^{sp}) + K_i \int_0^t (w_0(\tau) - w_0^{sp}) \mathrm{d}\tau$$

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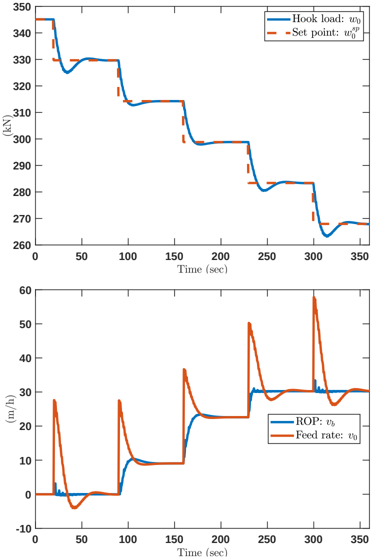

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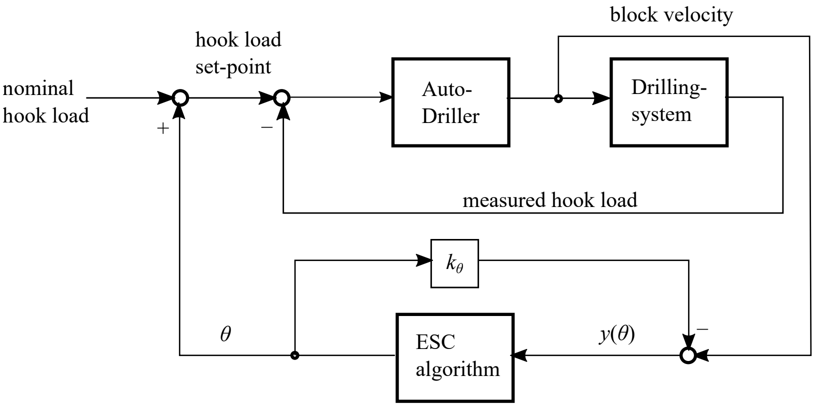

- System maps θ to $y(\theta)$.

Static map

- At equilibrium we find:

$$y(\theta) = \begin{cases} -k_\theta \theta, & \text{Phase I} \\ \frac{\omega_{\text{bit}} - K_a k_\theta}{K_a + \omega_{\text{bit}} k_v} \theta + K_y, & \text{Phase II} \\ -k_\theta \theta + d_b \omega_{\text{bit}}, & \text{Phase III} \end{cases}$$

$$K_y = \frac{\omega_{\text{bit}}}{K_a + \omega_{\text{bit}} k_v} \left(M_{HW} g - w_0^{nom} - w_{f*} \right)$$

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- Required assumptions:
  1. $0 < k_\theta < \frac{\omega_{\text{bit}}}{K_a}$
  2. $w_0^{nom} < M_{HW} g - w_{f*}$

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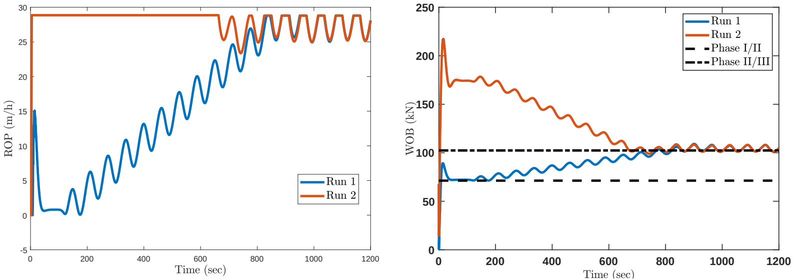
- Required assumptions:
  1. $0 < k_\theta < \frac{\omega_{\text{bit}}}{K_a}$
  2. $w_0^{nom} < M_{HW} g - w_{f*}$
- Then convergence to Phase II/III transition as a peak

Simulation



Drilling response with extremum seeking control started at 120 seconds.

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