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Port Function Based Modeling and Control of an Autonomously Variable Spring to Suppress Self-Excited Vibrations While Drilling

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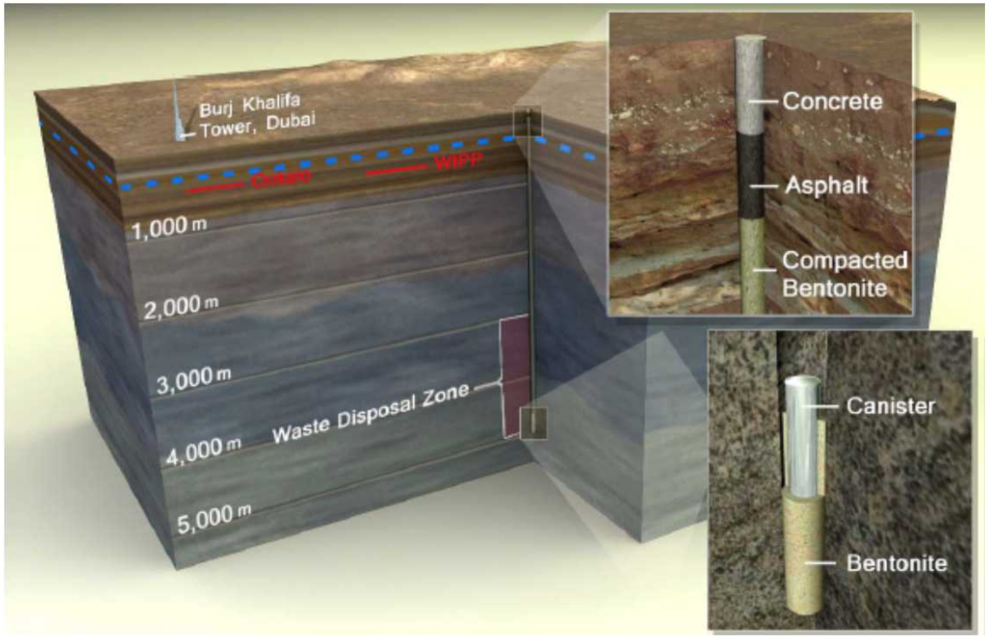
Drillstring Vibration Challenge

- Vibration in drillstring is a high-impact pathology for rock drilling
  - Inefficient drilling, equipment damage
  - Leading cause of non-productive time (Reid, 1995; Ledgerwood, 2010)

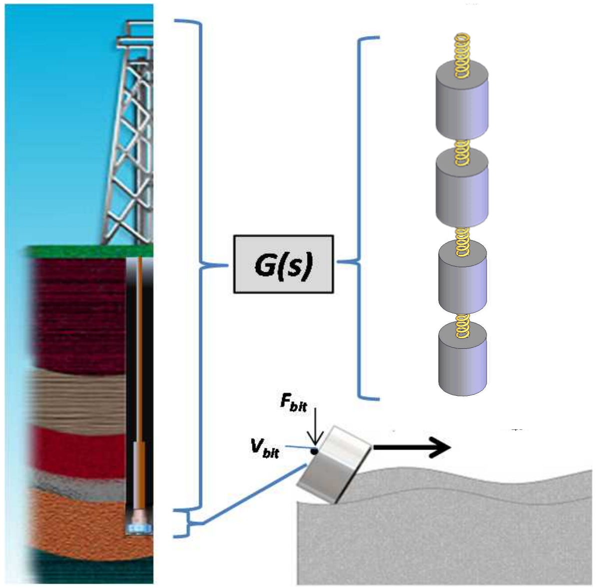
- Deeper holes mean more flexible drillstrings and greater possibility of vibration

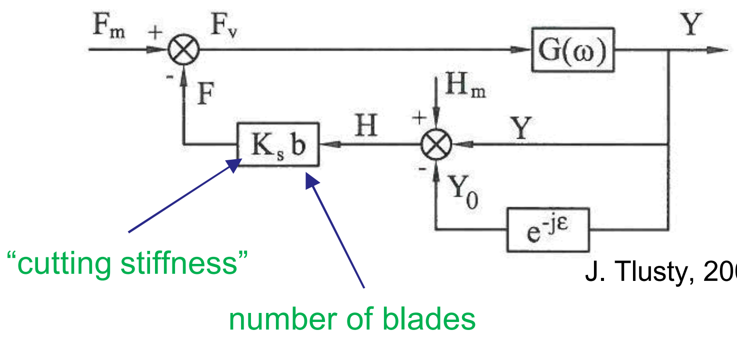
- Deep borehole disposal (Brady et al., 2012)
  - Concept to store high-level radioactive waste deep underground
  - Conceptual hole is 5 km deep into crystalline basement rock



Mechanics of Self-Excited Axial Vibration

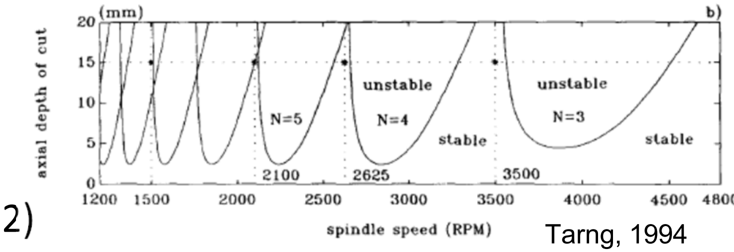
- Model for self-excited vibrations using Polycrystalline Diamond Composite (PDC) drag bits
- Instability (J. Tlusty et al.)
  - Derived from model for chatter in machine tools
  - Successive cutter passes introduce effective feedback delay
  - Unmodeled nonlinearities turn “instability” into stable limit cycles
- Resonant vibrations: separate but related
  - Nonlinearities obscure differences between unstable & resonant vibrations
- Stiffness varies with depth, shifting modes





J. Tlusty, 2000

Prior Work in Vibration Suppression



Tarng, 1994

- Work around / mitigate dynamics
  - Tailor bit design to drilling conditions (Wu, 2012)
    - Problem: Solution locked into hardware; ineffective for highly variable dynamics
  - Monitor & suppress chatter via mill spindle speed control (Tarng, 1994)
    - Problem: Limit performance, tough to measure down-hole

- Intelligently control dynamics
  - Vary stiffness (Dareing, 1990)
    - Vary the (force to position) transfer function *G(jω)*
      - Boosting real portion of *G* improves stability
      - Reduces transmissibility from bit to drillstring at problematic frequencies
    - Theory defines *necessary* conditions for unstable vibrations & showed those could be manipulated by varying stiffness near drill bit
  - Vary damping (Raymond, 2006)
    - Experiments showed that varying *stiffness* is impactful

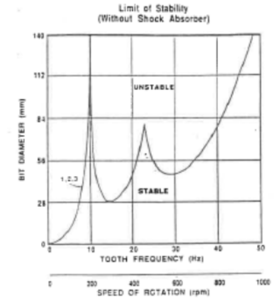


Fig. 9 Limit of stability (without shock absorber)

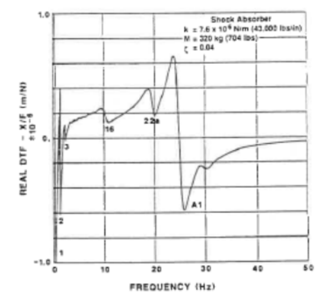


Fig. 10 Real part of direct transfer function (with shock absorber)

Dareing, 1990

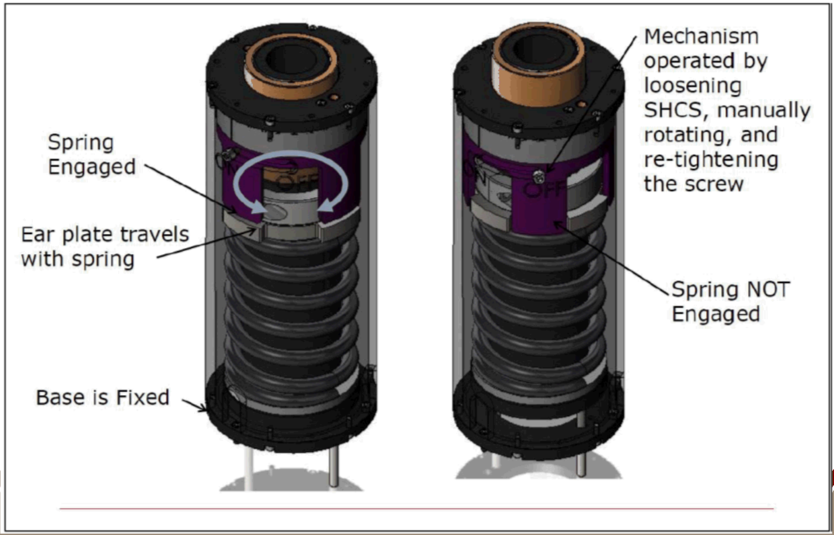
Consistently: varying stiffness near bit can suppress vibrations

Tool to Implement Variable Stiffness

- Goal: locally controlled, autonomous module to suppress vibration
  - Ideally no communications, only local measurements
  - Challenging operating environment (vibe, temp, noise, etc.)

- Conceptual tool design
  - 5 binary spring modules; loaded in parallel
  - 32 spring states

- Need: scheme for optimizing stiffness based on local measurements



System-Level Modeling – Drillstring Dynamics (1)

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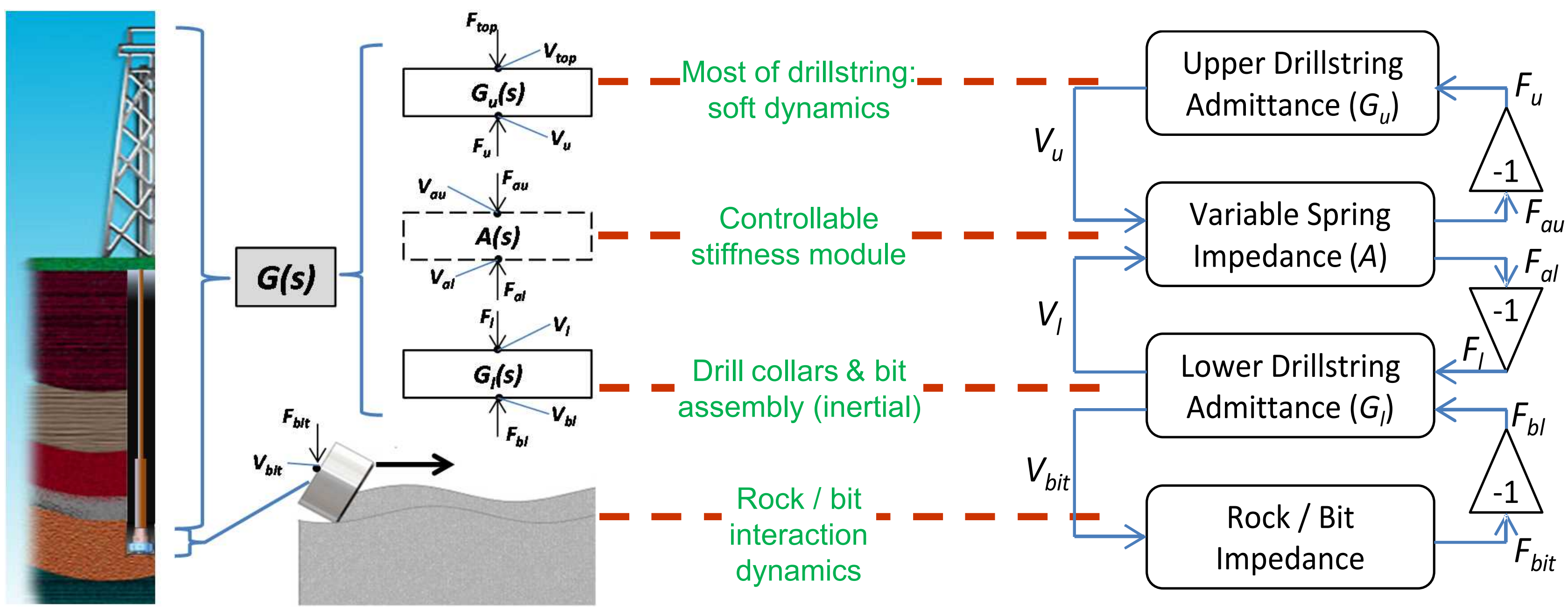
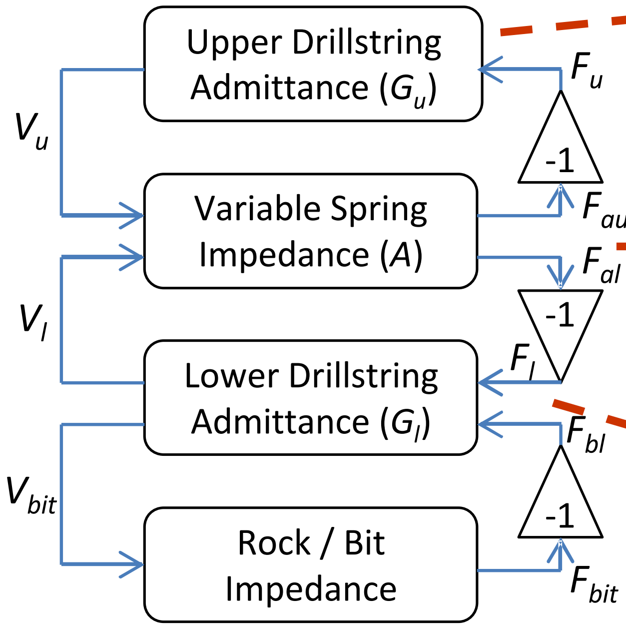
- Drillstring segments modeled with port functions
  - Mechanical impedance and admittance
  - Subsystem loading issues are handled automatically
  - Dynamics independent of instantaneous direction of power flow



System-Level Modeling – Drillstring Dynamics (2)

- Upper drillstring (G_u) modeled as second order system (m_u, b_u, k_u)
  - Can readily be replaced with more complex dynamics
- Controllable element (A) has variable spring k_{vs} and damping b_{vs}
- Lower drillstring (G_l) is mass m_l
- Joined via Newton's second law



$$G_u = \frac{V_u}{F_u} = \frac{s}{m_u s^2 + b_u s + k_u}$$

$$\begin{bmatrix} F_{au} \\ F_{al} \end{bmatrix} = A \begin{bmatrix} V_{au} \\ V_{al} \end{bmatrix} = \begin{bmatrix} \dfrac{b_{vs}s + k_{vs}}{s} & -\left(\dfrac{b_{vs}s + k_{vs}}{s}\right) \\ -\left(\dfrac{b_{vs}s + k_{vs}}{s}\right) & \dfrac{b_{vs}s + k_{vs}}{s} \end{bmatrix} \begin{bmatrix} V_{au} \\ V_{al} \end{bmatrix}$$

$$\begin{bmatrix} V_l \\ V_{bl} \end{bmatrix} = G_l \begin{bmatrix} F_l \\ F_{bl} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{m_l s} & \dfrac{1}{m_l s} \\ \dfrac{1}{m_l s} & \dfrac{1}{m_l s} \end{bmatrix} \begin{bmatrix} F_l \\ F_{bl} \end{bmatrix}$$

System-Level Modeling – Rock-Bit Interactions

- PDC drag bit model of Detournay
  - Models frictional and cutting (spring-like) forces between rock and bit
  - Restrict to drilling “region 2” (fully engaged cutter)
  - Only concerned with longitudinal portion – assume full torque is provided
- Compute reaction force F_{bit} in response to depth of cut at constant angular velocity ω; V_{bit} is rate of penetration
  - Relationships between scaled weight on bit (w) and scaled depth of cut (d)
  - At onset of region 2, $w=w_*$, $d=d_*$
  - Bit has full cross section with radius a
  - ζ and ε are constants that define cutting process (specific to rock & bit)

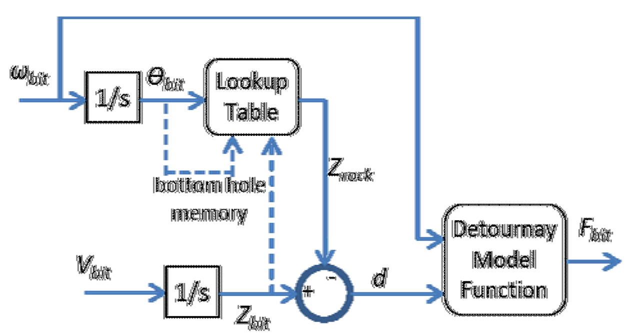
$$w = \frac{F_{bit}}{a} \qquad d = \frac{2\pi V_{bit}}{\omega}$$

$$w = \zeta\varepsilon(d - d_*) + w_*$$

Spring-like term

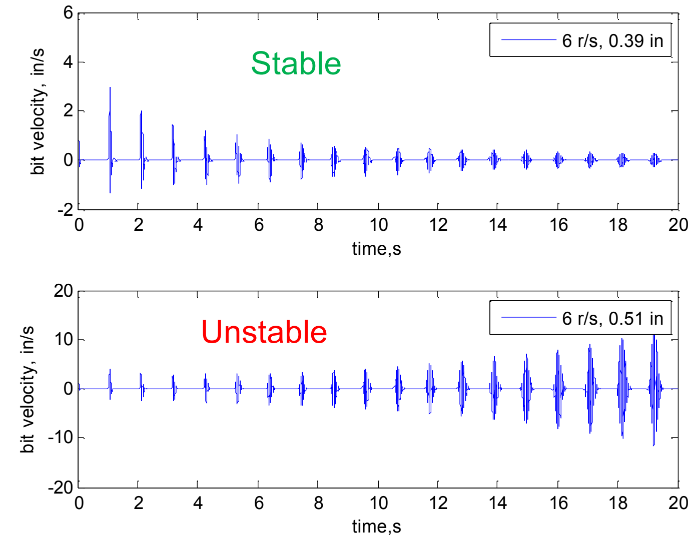
Coulomb friction term

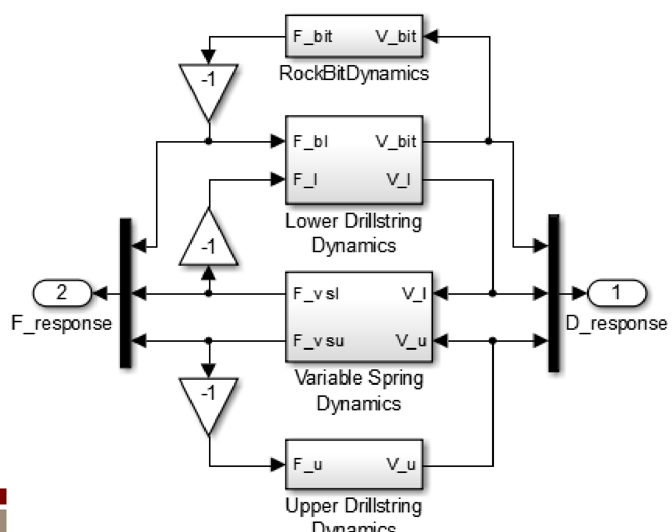
Together provide impedance function F_{bit}/V_{bit}

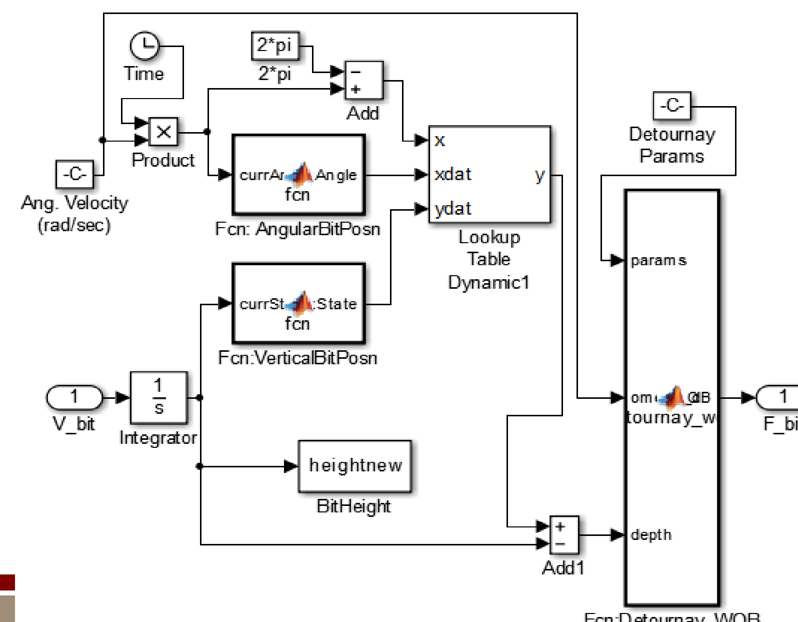


System-Level Modeling – Implementation

- Port functions integrated in Simulink
- Vary: ω, spring rate, bit radius *a*
- Initial bottom hole geometry provides excitation
- Define stability boundary in *a*
  - Increasing *a* increases effective stiffness
  - Unstable if vibrations increasing in amplitude after 20 seconds

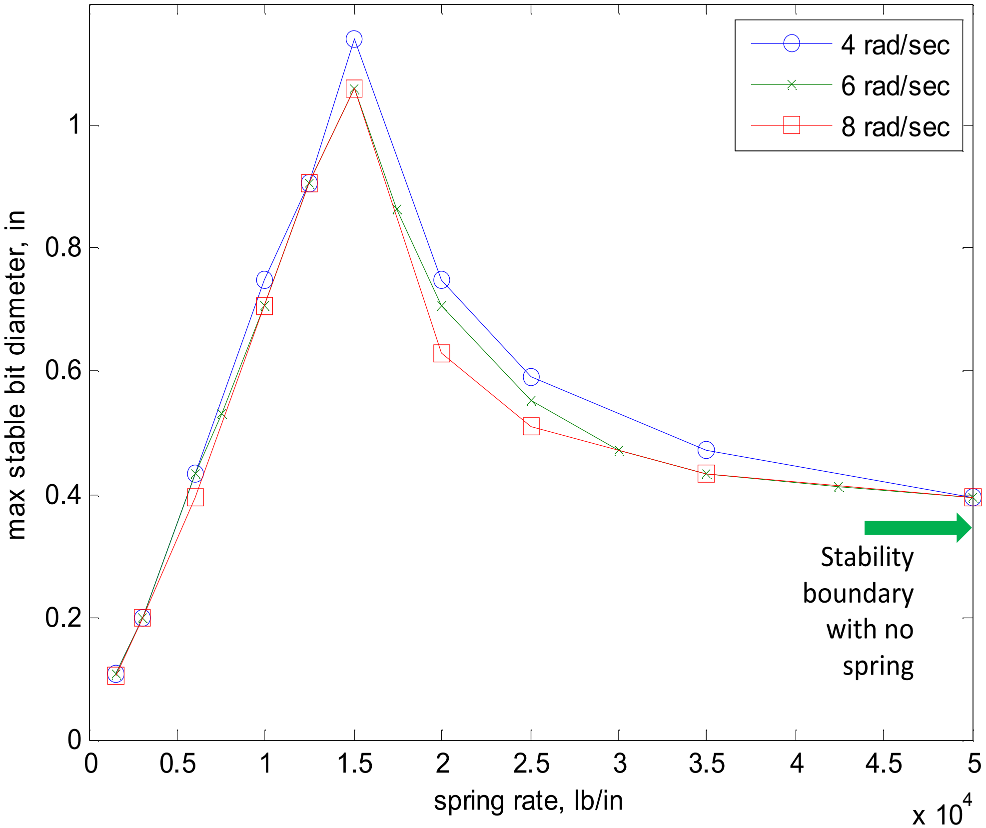






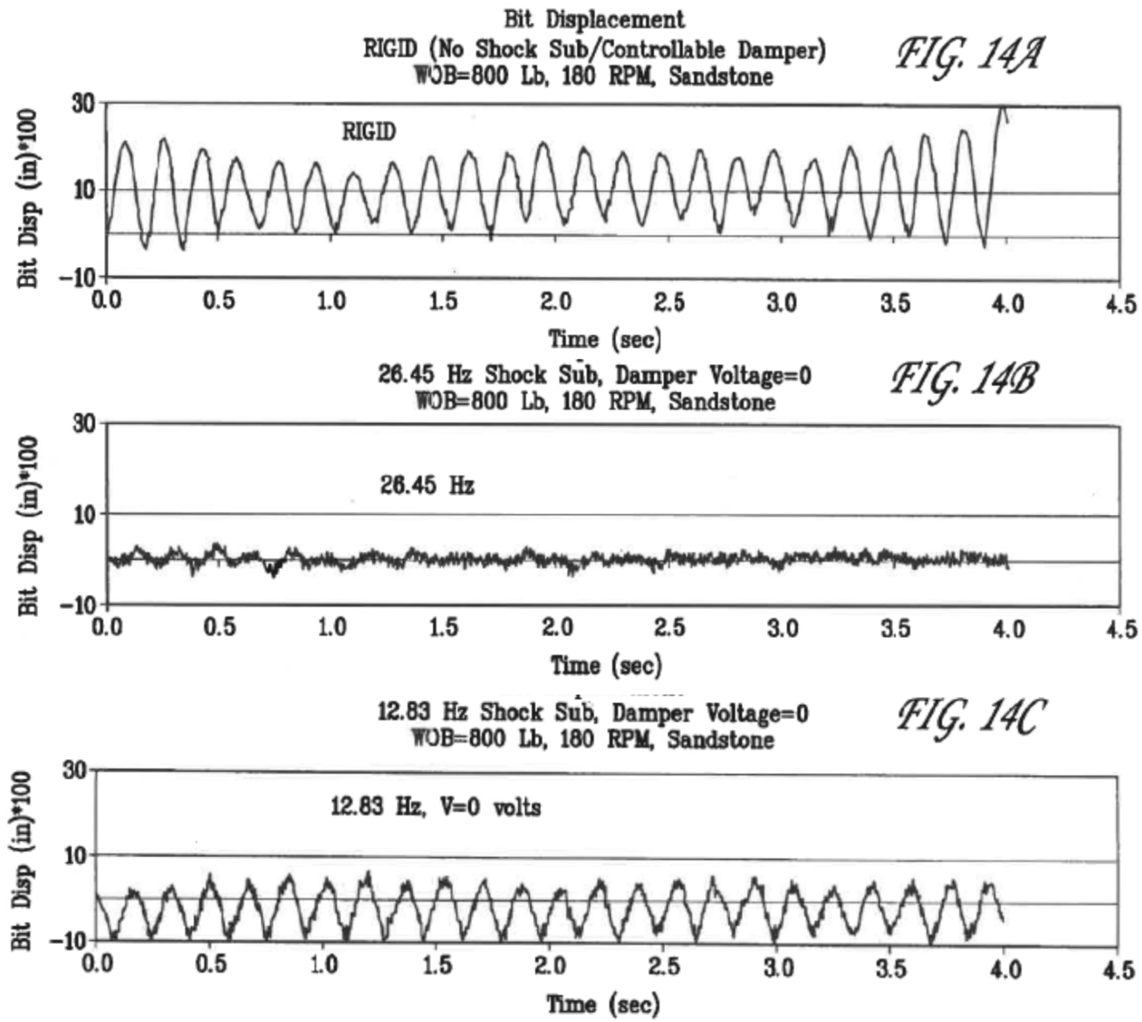
Results: Stability Limit vs. Stiffness

- Minimal variation with ω
- For large k_{vs}, boundary converges to “no spring” limit
- Most stable at intermediate k_{vs}; stable *a* 3x greater than baseline
  - Aligns with some prior published results (next slide)
- Very low stiffnesses are significantly *de*stabilizing
- Apparently two distinct stability limits that meet at 15klb/in



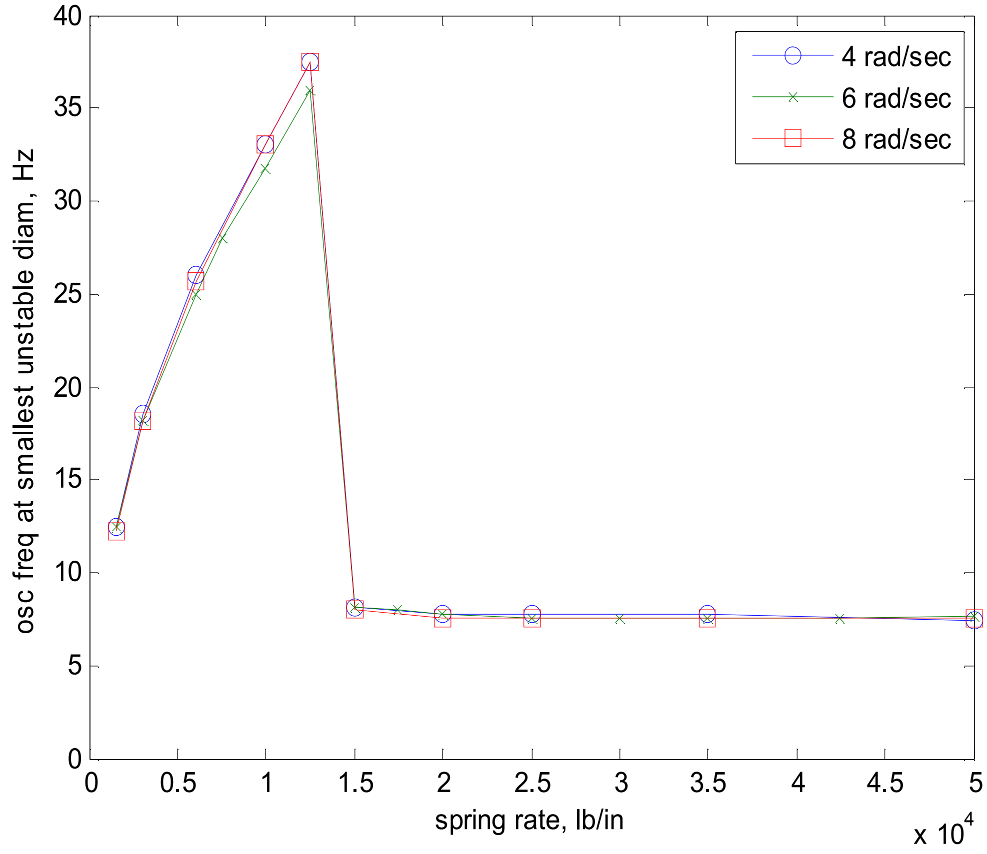
Stability vs. Stiffness – Prior Data

- Some prior experiments (Raymond et al. 2006) show intermediate stiffness reducing vibration more than high or low



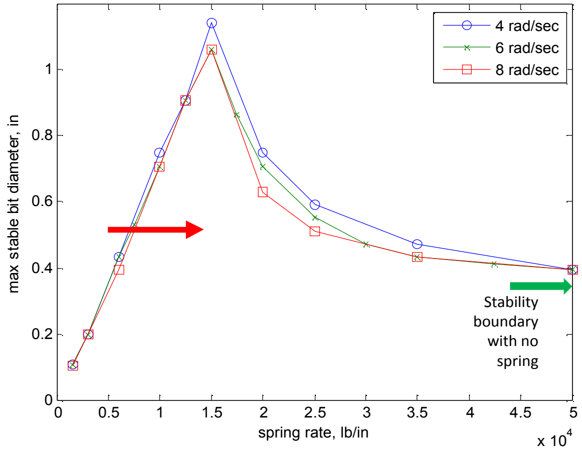
Results: Unstable Frequencies at Stability Boundary

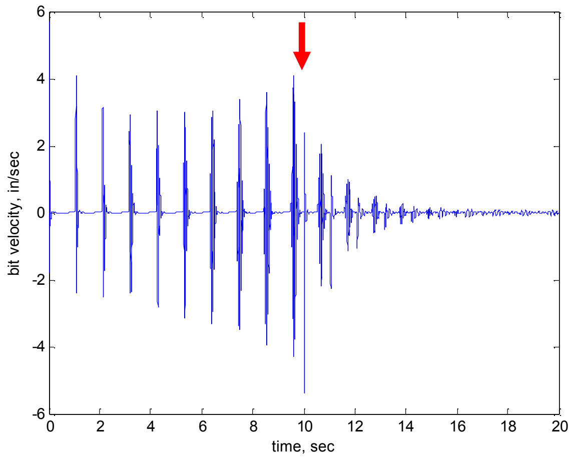
- Supports view of two distinct stability boundaries
- At low k_{vs}, frequency ~proportional to k_{vs}; new mode from controllable spring is unstable
- At higher k_{vs}, frequency relatively invariant; original drillstring mode is unstable
  - Harmonic frequency ~5.25 Hz
  - Interaction with rock stiffness pushes to ~7.5 Hz



Implications for Downhole Control

- Goal: switch the stiffness discretely when vibrations exceed threshold
  - Sim example: switch k_{vs} from 6 klb/in to 15 klb/in at t=10s

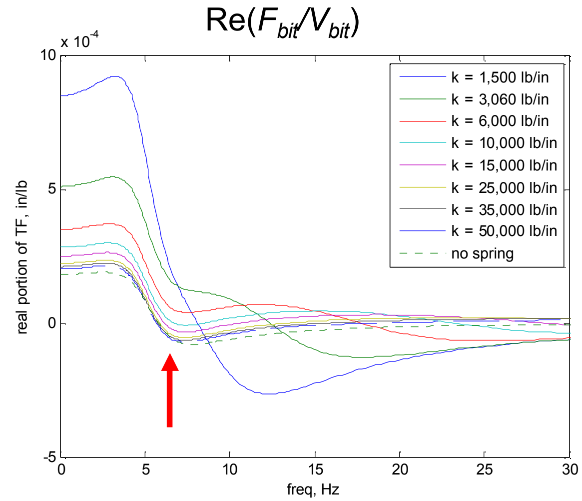


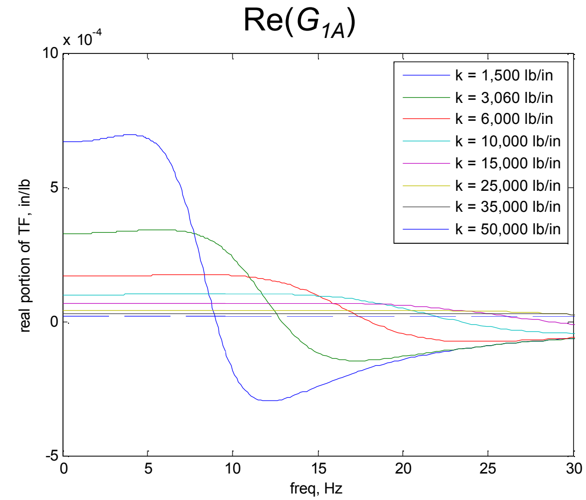


- Control challenge: identifying new k_{vs} value to switch to…
  - Without knowledge of drillstring dynamics
  - Without measurements except those taken locally

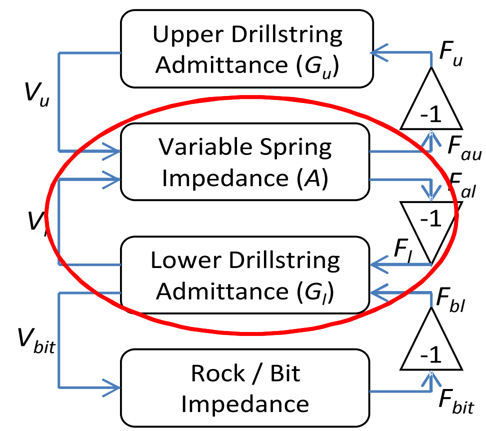
What Do Local Dynamics Predict About Overall Drillstring Dynamics?

- From Tlusty:
  - Boosting Re(F_{bit}/V_{bit}) at modal frequency is stabilizing
  - Soft springs help 7.5 Hz mode BUT destabilize at higher frequencies
  - Consistent with sim results





- If we know F_{bit}/V_{bit}, we can control spring to boost Re(F_{bit}/V_{bit}) at problematic frequencies
  - This requires knowledge of upper drillstring (G_u) dynamics
- However, we know TF for G_l and A quite well (G_{1A})
- Key features of Re(G_{1A}) correlate to features of Re(F_{bit}/V_{bit})
  - Freqs where Re(G_{1A}) curves cross zero are very close to freqs where Re(F_{bit}/V_{bit}) cross the "no spring" curve
  - This may be enough to estimate key features of Re(F_{bit}/V_{bit})



Potential Control Scheme

- Continuously measure downhole vibrations & analyze frequency content (e.g. PSD)
- Identify frequencies that contain power over a threshold
  - Store in slowly forgetting memory
- Select spring rate that optimizes benefit across the frequencies with observed powerful vibrations
  - E.g. maximize the minimum boost to *Re(G)* across the relevant frequencies
- Repeat continuously

Conclusions & Next Steps

- First combination of prevailing models for drilling self-excited vibrations and drag bit-rock interactions
- Use of simplified models reveals interesting things:
  - Intermediate stiffness values are optimal (confirms prior indications)
  - Key info may be extracted from just vibration freqs & local dynamics
  - May yield a local real-time control method
- Complex, challenging problem and much more is to be done:
  - Higher order system dynamics
    - Low-order models frequently represent key drilling dynamics, but will these results translate to higher order?
  - Experimental validations
  - Dealing with resonant vibrations as well as instability
  - Embedded control implementation & field-ready tool
  - Torsional & multi-axis vibration suppression