Primary funding is provided by

The SPE Foundation through member donations and a contribution from Offshore Europe

The Society is grateful to those companies that allow their professionals to serve as lecturers

Additional support provided by AIME
Tuning a Drilling Assembly Like a Violin

Dr. Jeffrey R. Bailey

ExxonMobil Upstream Integrated Solutions Company
How would a music concert sound if the musicians did not tune their instruments?
Which of these violins is tuned?

Damin Posse/946287238/Getty Images

Sjo/184329350/Getty Images
Drilling Assembly is More Complicated than a Violin

2\textsuperscript{nd} Order Differential Equation

Two Nodes

4\textsuperscript{th} Order Differential Equation

Possibly Many Nodes

Bottom Hole Assembly (BHA)
Nodal Points Critical to Lateral BHA Response

• What is the significance of a “nodal point”?
• What happens when the finger position changes on a violin?
• What happens when a nodal point moves on a Bottom Hole Assembly (BHA)?
Drilling Vibration Modes

**Torsional**
- Twisting motion extends from bit to surface
- Recent interest in High Frequency Torsional Oscillations (HFTO) due to related tool damage
- Mitigation: Soft Torque\textsuperscript{TM} / Soft Speed\textsuperscript{TM}, Tomax\textsuperscript{TM} tool
- Detection: EM TORAX Surveillance technology

**Axial**
- Axial vibes also travel full length of drill string
- More common with roller cone bits than PDC bits
- Axial shock subs available for decades
- Some association with HFTO in Unconventionals

**Lateral**
- Typically lateral vibes dissipate in lower string section
- Stabilizer placement, wall contact, and friction are key
- Few accepted mitigation paths, thus “opportunity rich”
- Vybs BHA Redesign to optimize stabilizer placement
“Turning a Bit on the End of a Sine Wave” (Fred Dupriest)

Experimental BHA test frame to evaluate directional tendencies

- Hydraulic top drive
- Two 3.5-inch collars
- Three stabilizer assemblies
- Instrumented steel target, hydraulic cylinder, and bit

Inspired dynamic modeling

Drilling Test Facility (Exxon 1992)
BHA Flexural Bending in Two Dimensions
Tuned Spacing: Making a Quieter Response
A Better Design: Smooth Response for RPM Range
Rotating BHA Model

Chatter is generated by the interference of contact points

BHAs are made up to “Top Drive” and run in hole from the left, viewed under blacklight.
Compare Short and Long-Spaced Contacts

Short Spacing – high contact forces and torques cause housing to rotate

Long Spacing – pipe motion less violent, reduced contact forces and torques do not cause housing to rotate
Amplified Response at Top of BHA

Transmitted Strain Response Decay (A)

Excitation at Bit

Muted Response at Top of BHA

Transmitted Strain Response Amplification (B)

Avoid Positive Feedback Gain

Amplified Response at Top of BHA

ZenRial/971031250/Getty Images
Tuning Drilling Assemblies with a Model

How can modeling help?

• Drilling Client and Vendor determine the tools
• Arrangement of tools has limited degrees of freedom
  ▪ Stabilization constraints, magnetic effects, electrical power, etc.
• Is the model simple and repeatable?
• Is the necessary data available?
• Can the model be applied to every BHA?

What is the “right” BHA design question?

What is the best arrangement of components for my well and operating conditions?
What Does The Model Consider?

BHA design
(OD, ID, Lengths, Nodes)

Parameter range
(RPM range, WOB)

Wellbore inclination
(mostly for statics)
Model Calculates Dynamic Sideforces at Contacts

- Static and dynamic contact forces are analogous in concept and mathematics

Relationship between static and dynamic contact forces

\[ F = wL - (-wL) = 2wL = \text{beam weight} \]

IADC/SPE-199613 • BHA Lateral Vibration Chatter Impedes Application of Weight to Bit
Calculate States for Each RPM and WOB Value

- Two BHAs, turbine with diamond impreg bit, dynamic states at 30 RPM & 20 klbs WOB
- Location of Red nodes creates disruptive pattern relative to Green nodes

IADC/SPE-199613 • BHA Lateral Vibration Chatter Impedes Application of Weight to Bit
Collect Results into “Vibration Indices”

- Factor of 8X lower vibration index for Green BHA at 30 RPM
- ROP increased 60% for Green BHA

Vibration Index values are calculated from the generated dynamic state bending moments.
Harmonic Analysis of the “Iron” Going in the Well

Relatively simple modeling process
- Identify nodal points of assembly
- No parameters to tune
- Include both dynamic and static modeling

“Forced Frequency Response”
- Apply lateral excitation at bit
- Calculate a “Vibration Index” of the bending strain energy
- Compare response of different BHA designs for identical excitation

Simple results to interpret
- Identify sweet spots and potential resonance risk
- Model results independent of geology, formations, drilling fluid, etc.
- Expect differences in drilling depending on conditions
Application Case Studies
Case No. 1: High-Angle Reaming-While-Drilling

- Redesigned BHA has 11m below Reamer tool to next contact
- Redesign to obtain lower vibration indices
- Vendor concerned by too much spacing between Reamer and stabilizer

"Vibration Index" ~ Bending Strain Energy Averaged along the BHA length

IPTC-18836 • How to Design a BHA Rotary Speed Sweet Spot
Good Drilling and Low Vibrations

Maintained WOB (24 klbs avg.) in soft formation at 88° hole angle
• 130 RPM (model sweet spot)
• 41 m/hr average drilling ROP
  • 69 m/hr instantaneous ROP
• Lateral vibrations < 2g RMS
• Low stick-slip, severity average < 1
  • Sticking ratio less than 0.4
• Zero axial vibrations

IPTC-18836 • How to Design a BHA Rotary Speed Sweet Spot
Steady “Making Hole” & Exemplary Performance

3X ROP vs. Average of 21 Prior Offsets

IPTC-18836 • How to Design a BHA Rotary Speed Sweet Spot
Additional Hole Drilling-While-Reaming Examples

- Hole Enlargement While Drilling (HEWD) successfully performed in Kurdistan using Vibration Analysis on Alquosh-1 well for two intervals:
  - 14-3/4” x 17” HEWD with an average ROP of 6.5 m/hr
  - 8-1/2” x 9-1/2” HEWD with an average ROP of 4.5 m/hr

- Longest and fastest HEWD ever recorded in Iraq

- Savings of 12 days of rig time by avoiding a separate hole enlargement run on both hole sections

- Provides ability to strengthen casing design with additional large strings without the added cost of a hole enlargement run

- Delivered a quality hole with minimal shocks and vibrations and minor bit and BHA wear in a harsh drilling environment
Case No. 2: Motor BHA Design

Two design changes:
• Remove contact below motor
• Move roller reamer above two joints of heavyweight pipe

Redesigned BHA vibration indices lower than Standard BHA
Faster Cycle Time, Better Performance

- Eliminated tool failures
- Improved bit dulls
- Overall 36% increase in daily footage

Redesigned BHA reduces MSE < 100 ksi
- Mechanical Specific Energy (MSE) measures the amount of work expended to drill rock

SPE 139426 • Managing Drilling Vibrations Through BHA Design Optimization
Lateral Vibration and MSE Data

- Histograms of lateral acceleration and MSE data for two wells
- Redesigned BHA demonstrated lower lateral vibrations and lower MSE

<table>
<thead>
<tr>
<th>Well</th>
<th>Standard BHA</th>
<th>Redesigned BHA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LatMax (g)</td>
<td>MSE (10^5 psi)</td>
</tr>
<tr>
<td>Well 1</td>
<td>2g</td>
<td></td>
</tr>
<tr>
<td>Well 5</td>
<td>2g</td>
<td></td>
</tr>
</tbody>
</table>

SPE 139426 • Managing Drilling Vibrations Through BHA Design Optimization
Case No. 3: Turbine BHA / Diamond Impreg Bit

T-01 design for three runs
- ROP declined but bits pulled with no wear
- Case for change

Used T-02 based on vibration model results
- Removed one collar and stabilizer
- ROP improved
- Five runs to TD

SPE 135439 • Design Tools and Workflows to Mitigate Drilling Vibrations
Better Drilling Results with Optimized BHA

- ROP Increased 60%
- Run Hours Up 68%
- Interval Length Up 150%
- MSE Decreased 30%

**Bit Grades**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-01</td>
<td>T-02</td>
</tr>
<tr>
<td>1-1-WT</td>
<td>7-8-NR</td>
</tr>
<tr>
<td>2-4-WT</td>
<td>4-4-NR</td>
</tr>
<tr>
<td>1-1-WT</td>
<td>8-8-CR</td>
</tr>
<tr>
<td>5-5-WT</td>
<td></td>
</tr>
<tr>
<td>3-3-WT</td>
<td></td>
</tr>
</tbody>
</table>

SPE 135439 • Design Tools and Workflows to Mitigate Drilling Vibrations
Case No. 4 Rotary Steerable BHA Redesign

- Difference between two designs is the highlighted sub below LWD tool
  - Increases span length
  - Reduces effective OD

- Lower vibration indices for BHA-1B, with sweet spot ~160 RPM

Schematics of BHA Designs
Population Distribution of Lateral Vibrations

BHA-1A average: 1.8 g

BHA-1B average: 0.6 g

SPE 163503 • Design Evolution of Drilling Tools to Mitigate Vibrations
Comparison of Measured Data

Lateral Vibration Measurements vs. RPM and WOB

- Both sweet spot rotary speeds are confirmed by lateral vibe data
- BHA-1A has less lateral stability than BHA-1B for high WOB

SPE 163503 • Design Evolution of Drilling Tools to Mitigate Vibrations
Case No. 5  BHA Design Affects Borehole Quality

Three BHA designs to drill 17½-inch hole and open to 20-inch in one pass

- Vibration indices suggest that Red UR BHA would be significantly worse than Green UR BHA
- Blue Bi-Center BHA looks good too

Run 1a/1b
Run 2a/2b
Run 3

BHA Strain
Transmitted Strain
Stab Sideforce
Endpoint Curvature
Case No. 5  BHA Design Affects Borehole Quality

Result - strong correlation of borehole enlargement with indices
(Note that interval was drilled with NAF fluid)

<table>
<thead>
<tr>
<th>Color</th>
<th>Bit Run</th>
<th>Footage</th>
<th>ROP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>1a</td>
<td>813 ft</td>
<td>45.2 ft/hr</td>
</tr>
<tr>
<td>Red</td>
<td>1b</td>
<td>914 ft</td>
<td>43.5 ft/hr</td>
</tr>
<tr>
<td>Green</td>
<td>2a</td>
<td>1094 ft</td>
<td>25.0 ft/hr</td>
</tr>
<tr>
<td>Green</td>
<td>2b</td>
<td>1164 ft</td>
<td>25.3 ft/hr</td>
</tr>
<tr>
<td>Blue</td>
<td>3</td>
<td>2486 ft</td>
<td>21.8 ft/hr</td>
</tr>
</tbody>
</table>

Extremely stable BHA and Bi-Center bit run; Gauge hole
Consider a BHA with following parameters:

- Rotary Steerable System
- MWD for Directional and Communication
- Two LWD tools for Formation Evaluation

How do we redesign this BHA and tools to achieve lower vibration indices?
Step 1: Combine or Separate Contacts

Preferred approach: Combine LWD1 and LWD2
Alternate approach: Spacer between LWD1 & LWD2

Combination of tools is best

LWD1 and LWD2 Spacing

Significant Reduction in Index Values

SPE 163503 • Design Evolution of Drilling Tools to Mitigate Vibrations
Step 2: Reduce Distance to Near Bit Support

Move near bit support closer to bit
• Similar in concept to seeking long gauge bit

Close contact to bit is good
Step 3: Increase Near Bit Stability

Remove Flex Sub below fourth contact point
- Stiffness up to 4\textsuperscript{th} contact governs lateral stability

**Increase Nearbit Stiffness**

**Significant Additional Reduction**

Not always feasible with current tools

---

SPE 163503 • Design Evolution of Drilling Tools to Mitigate Vibrations
Step-by-Step Guide to Lower Vibration Indices

Just three steps! Reduced index from 100,000 to 50

Field results confirm what model is telling us

LWD Spacing, Closer Nearbit Contact, No Flex

Huge Reduction in Index Values

Combined effects

SPE 163503 • Design Evolution of Drilling Tools to Mitigate Vibrations
Data Required for Analysis

BHA data sheet
Specs for each tool
  • OD, ID, Length, Contacts
Target operating parameters
  • WOB, RPM, Flow rate if motor
Hole Inclination Angle
Timing for analysis
How do we get this technology in every foot of hole we drill?

It’s All About The Workflow!

IPTC-18836 • How to Design a BHA Rotary Speed Sweet Spot
SPE 135439 • Design Tools and Workflows to Mitigate Drilling Vibrations
SPE 139426 • Managing Drilling Vibrations Through BHA Design Optimization
SPE/IADC 163503 • Design Evolution of Drilling Tools to Mitigate Vibrations
IADC/SPE-199613 • BHA Lateral Vibration Chatter Impedes Application of Weight to Bit
IADC/SPE 112650 • Drilling Vibrations Modeling and Field Validation
Benefits of BHA Redesign?

1. Increase drilling efficiency
   • More footage per day

2. Lower NPT (time + money)
   • Fewer trips to change out tools
   • Fewer tools required per interval

3. Reduce risk
   • Fewer days on the well = lower risk

4. Reduce cost
   • Sum the above to get total savings
Key Takeaways

• Drilling performance does vary with BHA design

• A well-framed harmonic analysis leads to insights on effective BHA Redesign techniques
  • “Management of BHA Contact Spacing”

• Sweet spot rotary speed ranges can be targeted through adjusting contact locations
  ▪ Just as a Musician Tunes a Stringed Instrument!
Thank you for your attention.

Are there any questions?
Your Feedback is Important

Enter your section in the DL Evaluation Contest by completing the evaluation form for this presentation
Visit SPE.org/dl

#SPEdl

Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl