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Tuning a Drilling Assembly Like a Violin

Dr. Jeffrey R. Bailey

ExxonMobil Upstream Integrated Solutions Company

Society of Petroleum Engineers
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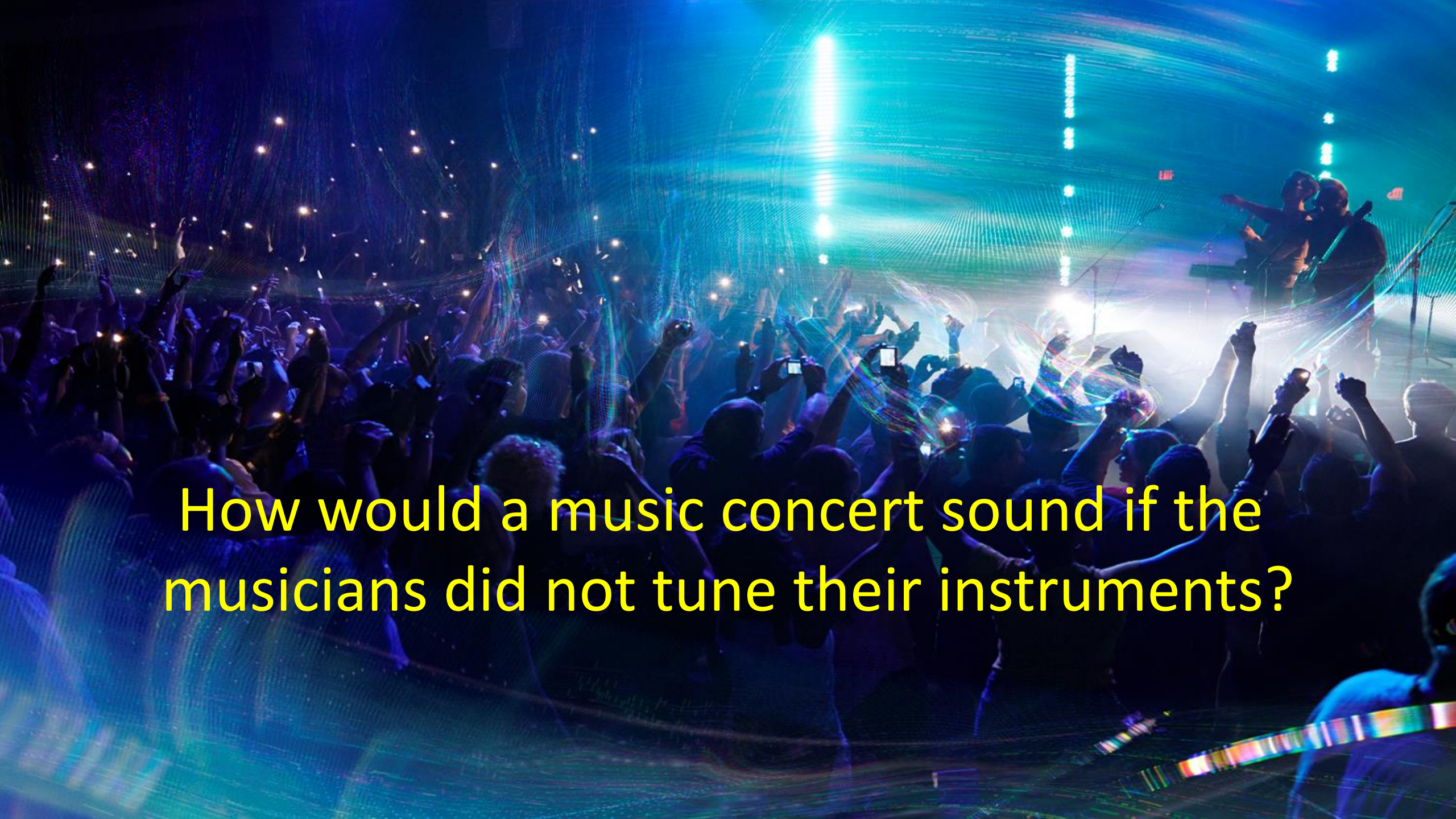

How would a music concert sound if the musicians did not tune their instruments?

Which of these violins is tuned?

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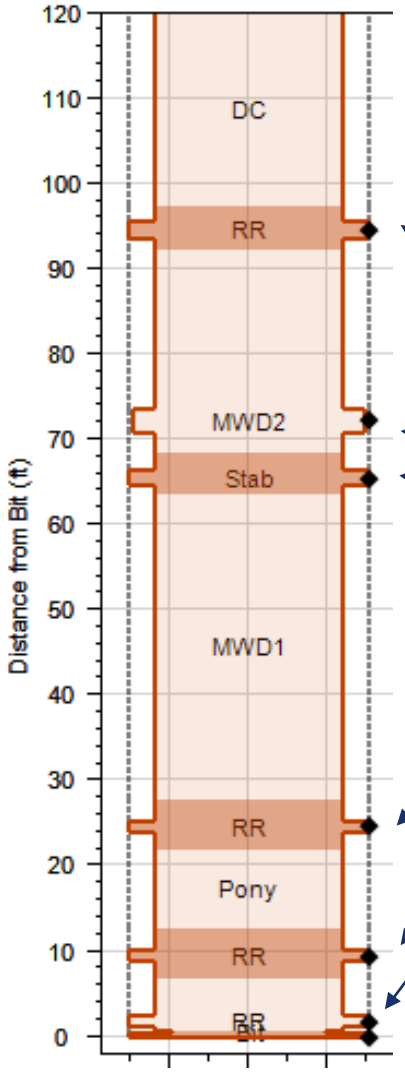
Drilling Assembly is More Complicated than a Violin

2nd Order Differential Equation

Two Nodes

Sjo/184329350/Getty Images



4th 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)?

Vladimir Serov/532032711/Getty Images

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Drilling Vibration Modes

Torsional

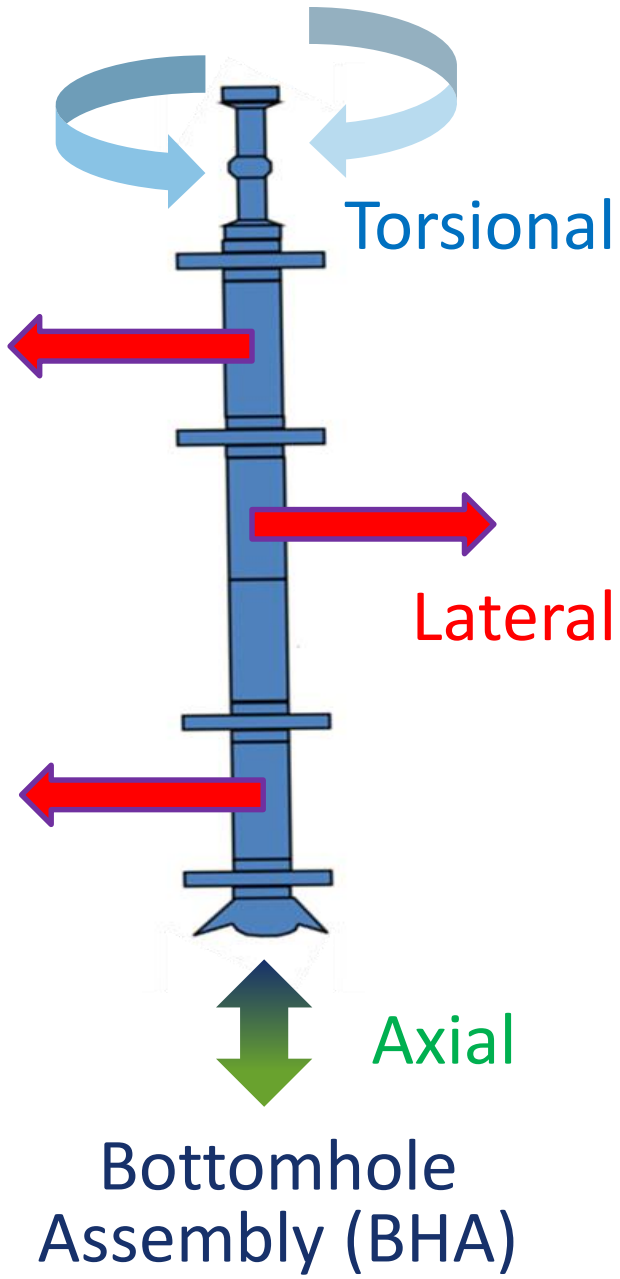
- Twisting motion extends from bit to surface
- Recent interest in High Frequency Torsional Oscillations (HFTO) due to related tool damage
- Mitigation: Soft Torque™ / Soft Speed™, Tomax™ tool
- Detection: EM TORAX Surveillance technology

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



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“Turning a Bit on the End of a Sine Wave” (Fred Dupriest)

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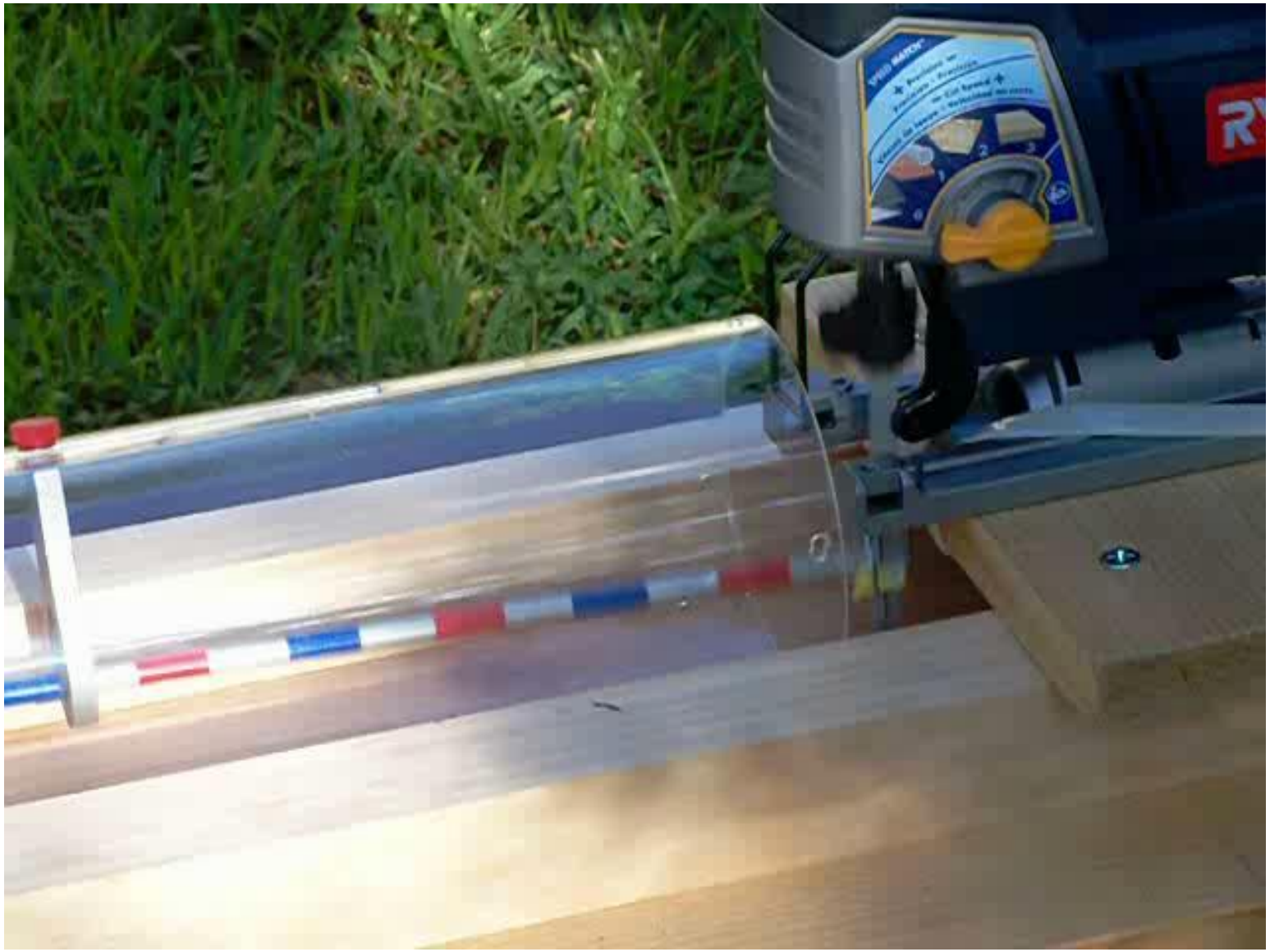
Experimental BHA test frame to evaluate directional tendencies

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

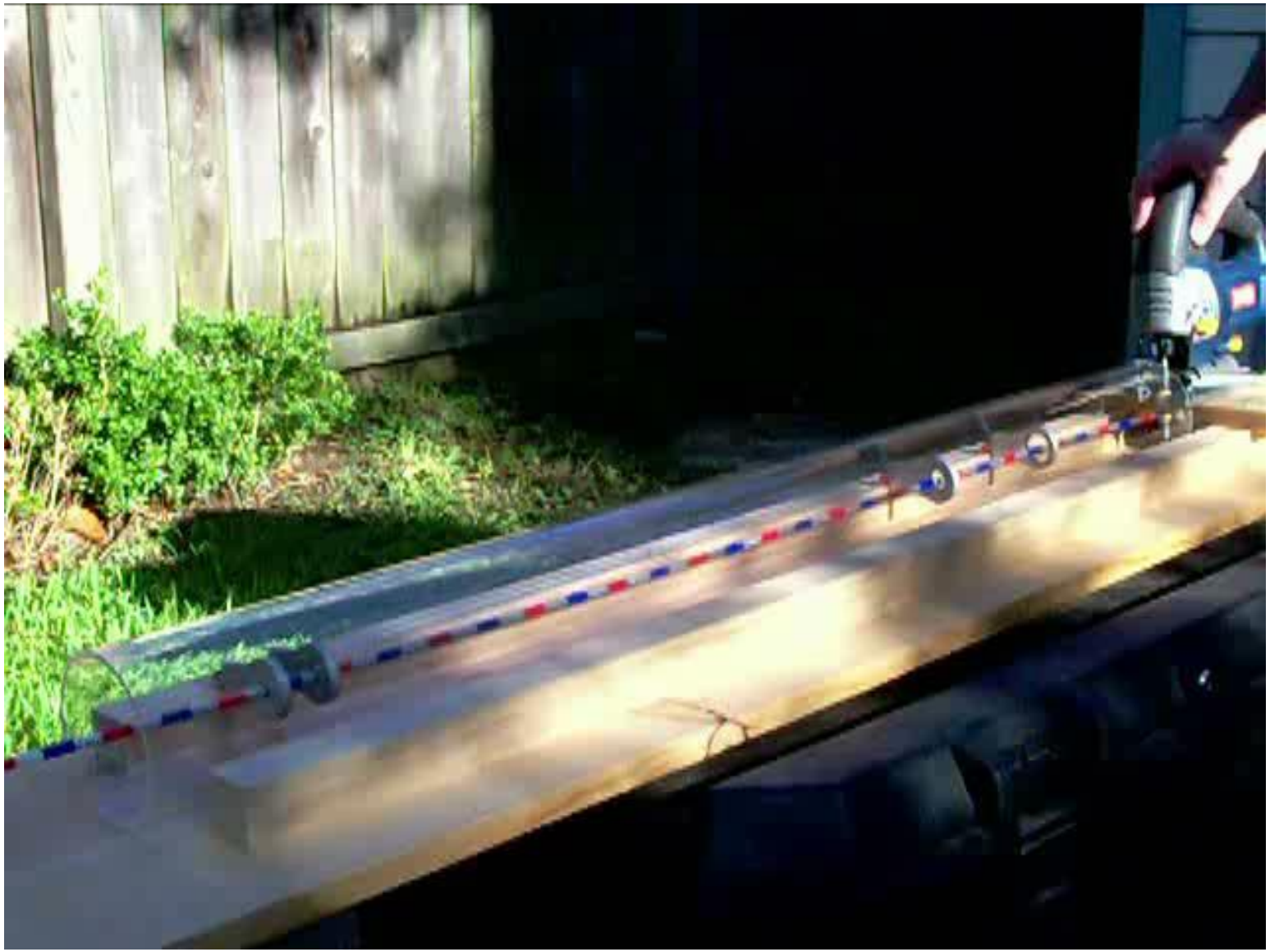
Inspired dynamic modeling

Drilling Test Facility (Exxon 1992)

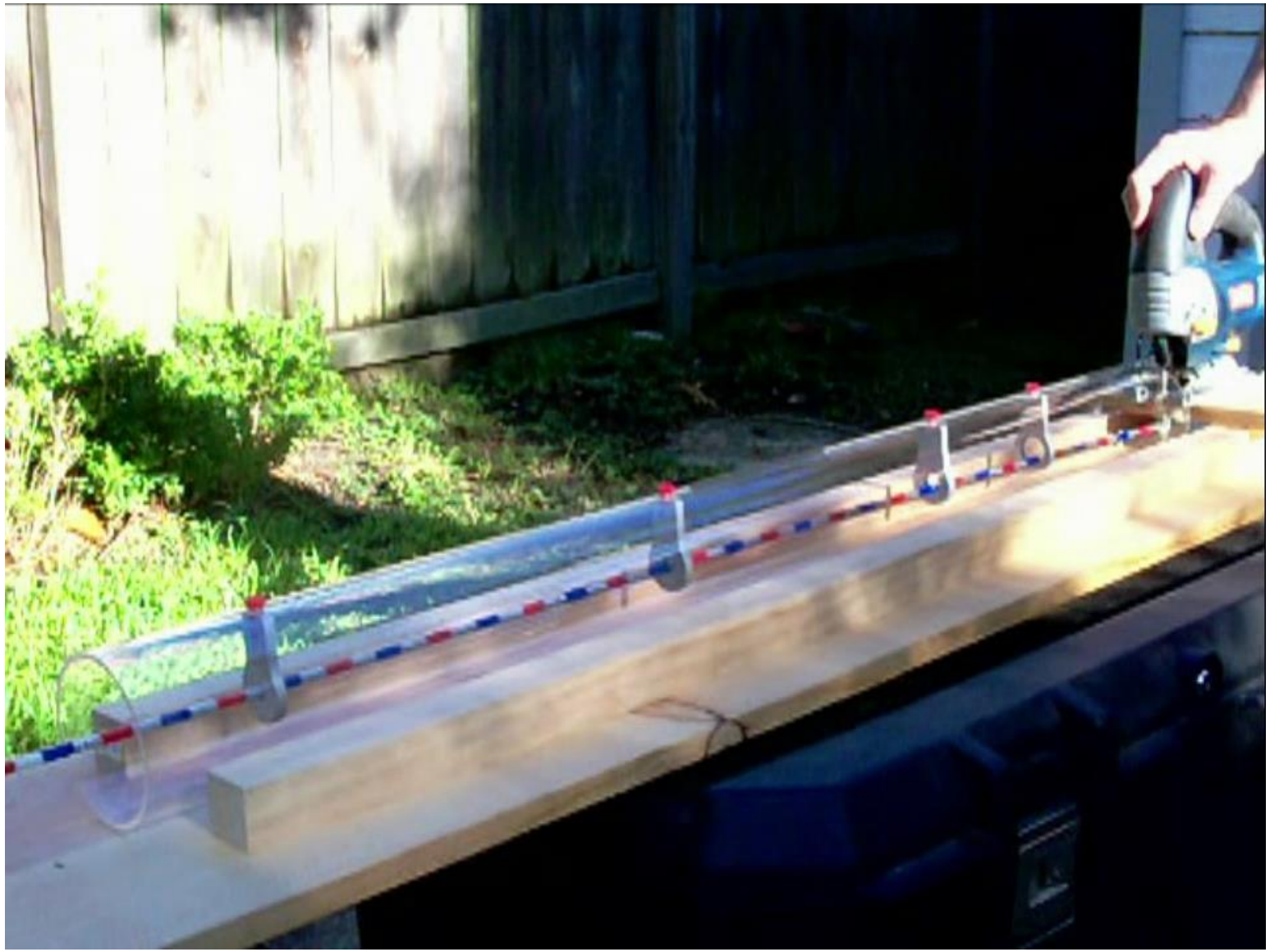
BHA Flexural Bending in Two Dimensions



Tuned Spacing: Making a Quieter Response

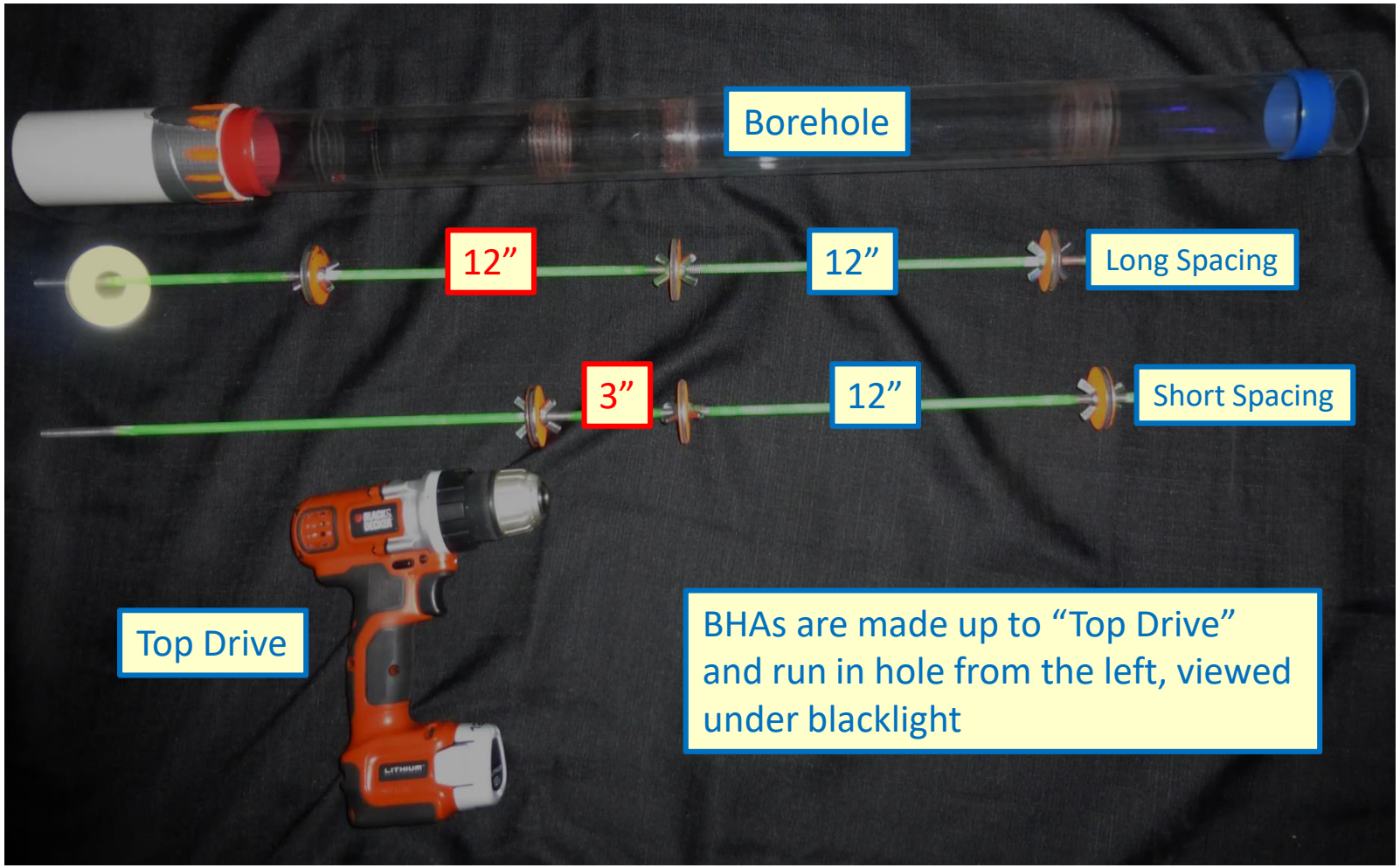


A Better Design: Smooth Response for RPM Range

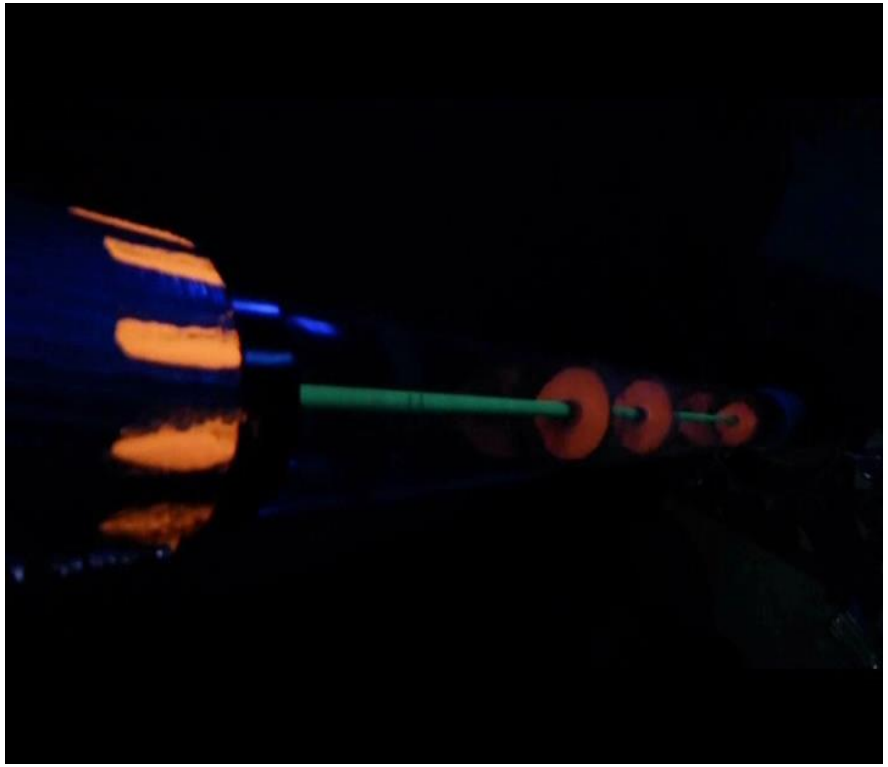


Rotating BHA Model

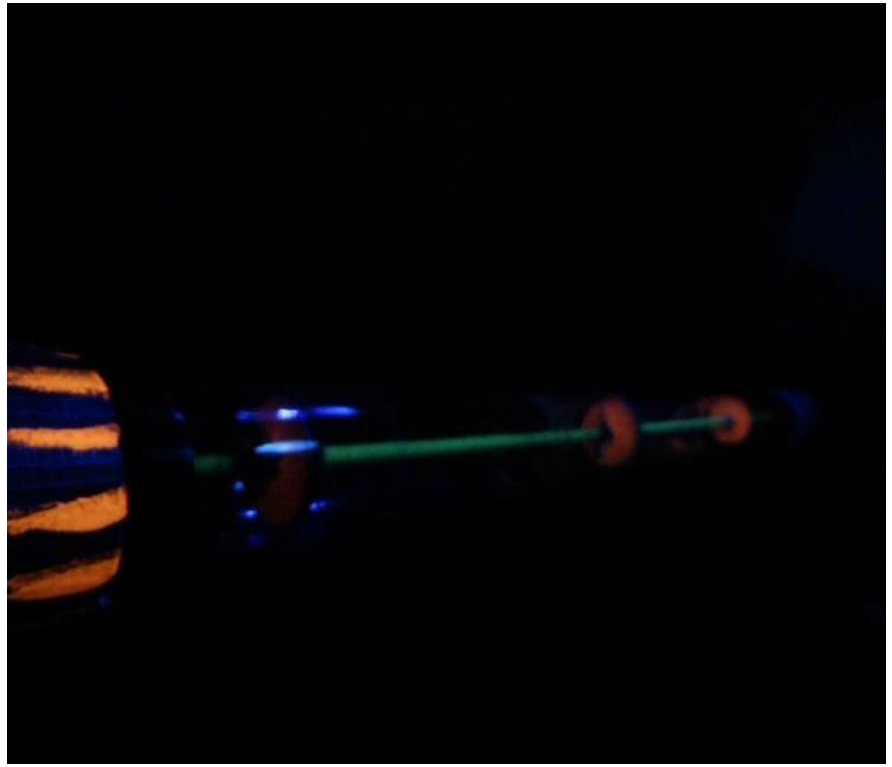
Chatter is generated by the interference of contact points



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

Transmitted Strain Response Decay (A)

Transmitted Strain Response Amplification (B)

Excitation at Bit

Muted Response at Top of BHA

A

B

Amplified Response at Top of BHA

Avoid Positive Feedback Gain

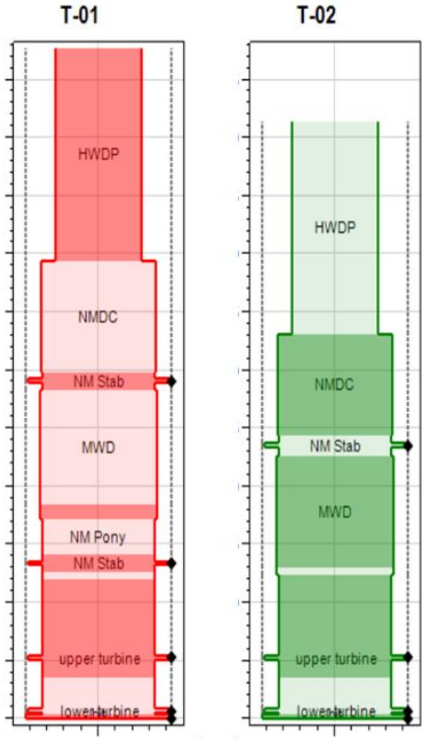
ZenRial/971031250/Getty Images

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?

bagi1998/175438654/Getty Images

What Does The Model Consider?

BHA design

(OD, ID, Lengths, Nodes)

Drill String used: 850-01

Read Only Data:

Comp. Marker	Comp. Type	Vendor	Label	Nom. Size (in)	Body OD (in)	Body ID (in)	Length (ft)	Cumulative Length (ft)	Blade OD (in)	Neck Length (ft)	Blade Length (ft)	Bit to Node Length (ft)	Steel Wt. Per Length (lb/ft)	Wt. Per Length (lb/ft)	Comp. Wt. (lbs)	Cumulative Wt. (lbs)	Modulus (ksi)
Top of BHA	Collar		DC		6.750	2.250	59.06	251.44	6.890				108.11	108.00	6377.95	25655.44	29000.0
	Collar		DC		6.750	2.250	59.06	192.39	6.890				108.11	108.00	6377.95	19277.48	29000.0
Nodal Point	Stabilizer		SADN		6.750	2.250	18.70	133.33	8.500	10.892	1.800	121.54	108.11	90.00	1683.07	12899.53	29000.0
	Collar		Sonic		6.750	3.290	23.79	114.63	6.890				92.73	105.00	2497.54	11216.46	29000.0
Nodal Point	Stabilizer		StethScop		6.750	2.810	31.00	90.85	8.500	25.361	1.800	64.59	100.55	90.00	2790.35	8718.92	29000.0
	Collar		TeleScope		6.750	5.109	27.40	59.84	6.772				51.95	90.00	2465.55	5928.57	29000.0
Nodal Point	Stabilizer		ILS		6.750	2.813	4.99	32.45	8.500	2.428	1.660	29.19	100.50	140.00	698.16	3463.01	29000.0
	Collar		ARC		6.750	2.810	21.42	27.46	7.598				100.55	101.00	2163.81	2764.85	29000.0
Nodal Point	Stabilizer		NBStab		6.500	2.250	4.92	6.04	8.500	2.592	1.660	2.61	99.27	99.00	487.20	601.04	29000.0
Nodal Point	Bit		bit		6.500	2.252	1.12	1.12	8.500	0.459	0.490		99.24	102.05	113.83	113.83	29000.0

Parameter range

(RPM range, WOB)

General | Drill String | Drill String Selection | WellPath

Calculation Setup

Calculation Type: Flex

☑ Run Statics

Flex Mode: 1

Rotary Speed: rpm

Weight on Bit: 25000.0 lbs

Fluid Density: 12.00 ppg

Sensitivity

☑ Calculate Vibrational Indices

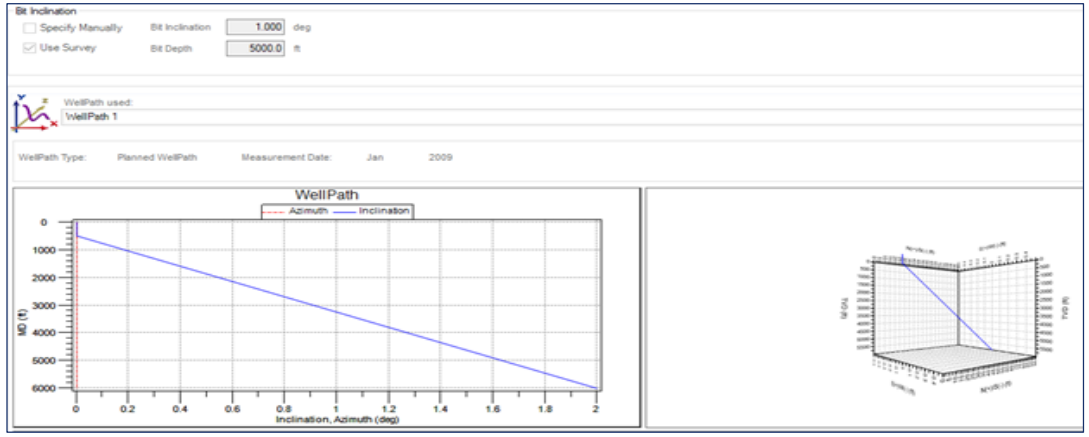
Max Flex Mode: 2

☑ Include WOB Sensitivity

RPM Start	60.0	rpm	WOB Start	0.0	lbs
RPM Stop	180.0	rpm	WOB Stop	40000.0	lbs
RPM Step	2.0	rpm	WOB Step	20000.0	lbs

Wellbore inclination

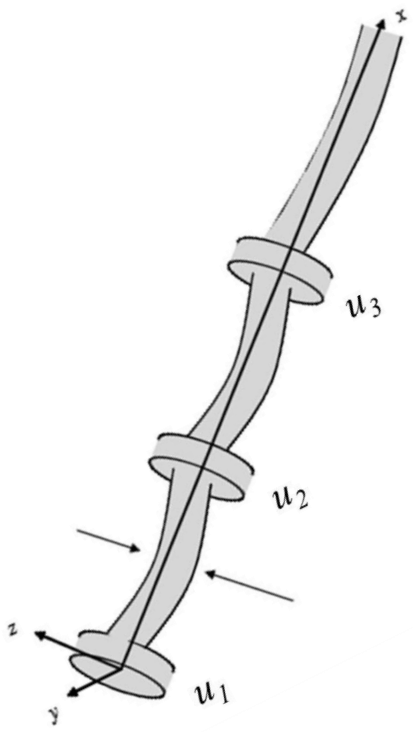
(mostly for statics)

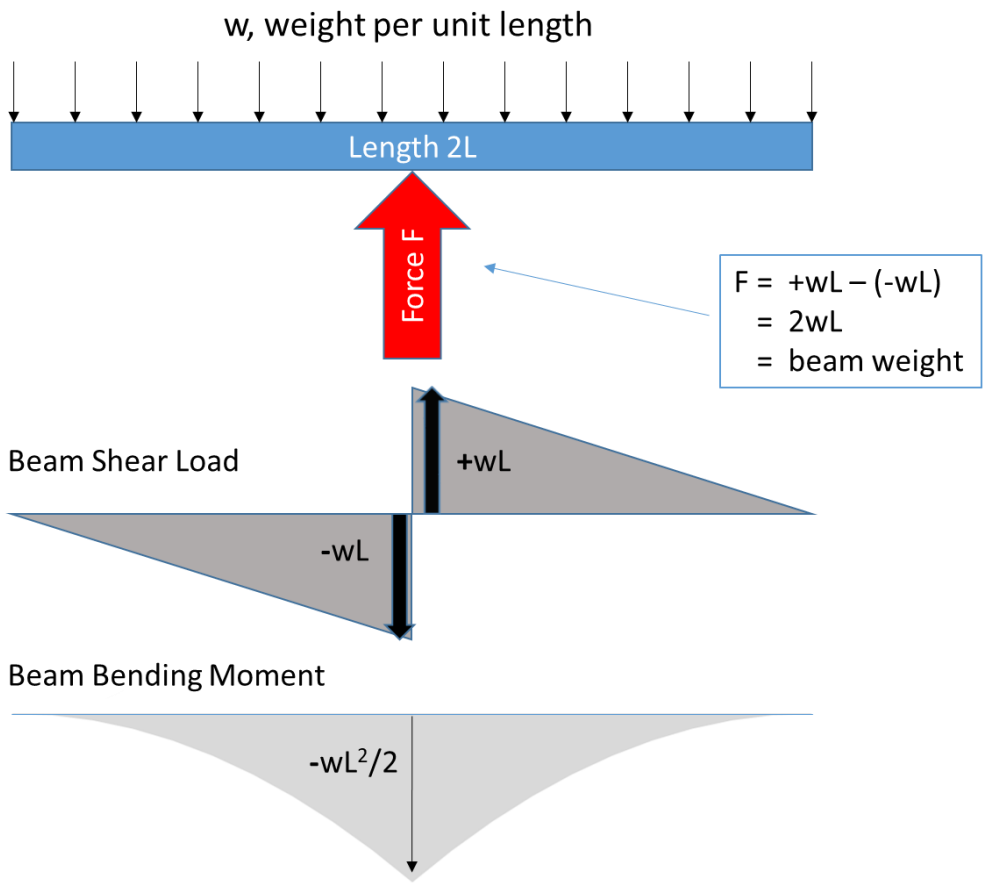


Model Calculates Dynamic Sideforces at Contacts

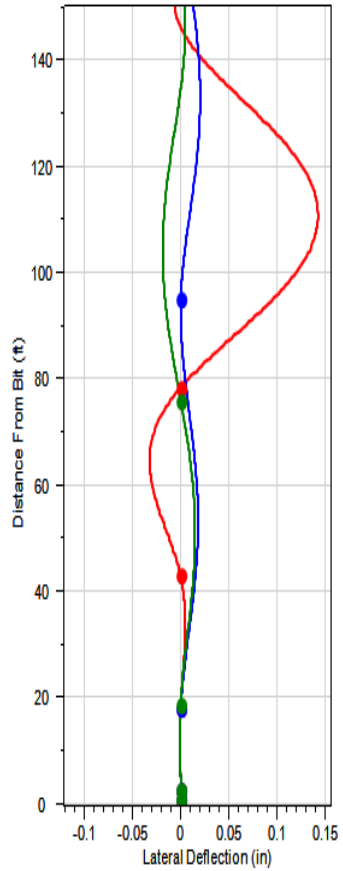
- Static and dynamic contact forces are analogous in concept and mathematics

Relationship between static and dynamic contact forces

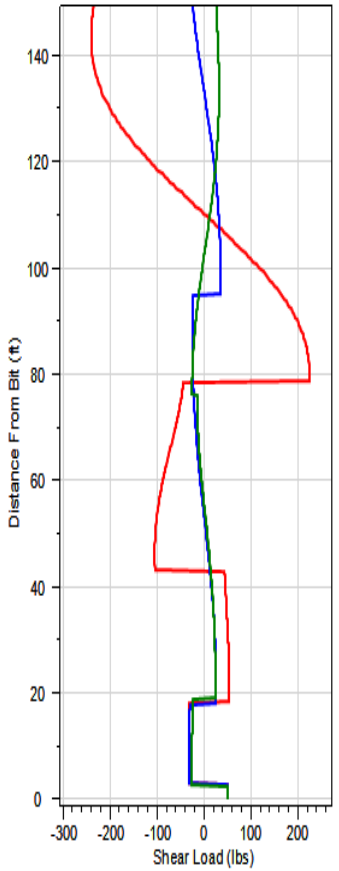




Lateral Deflection

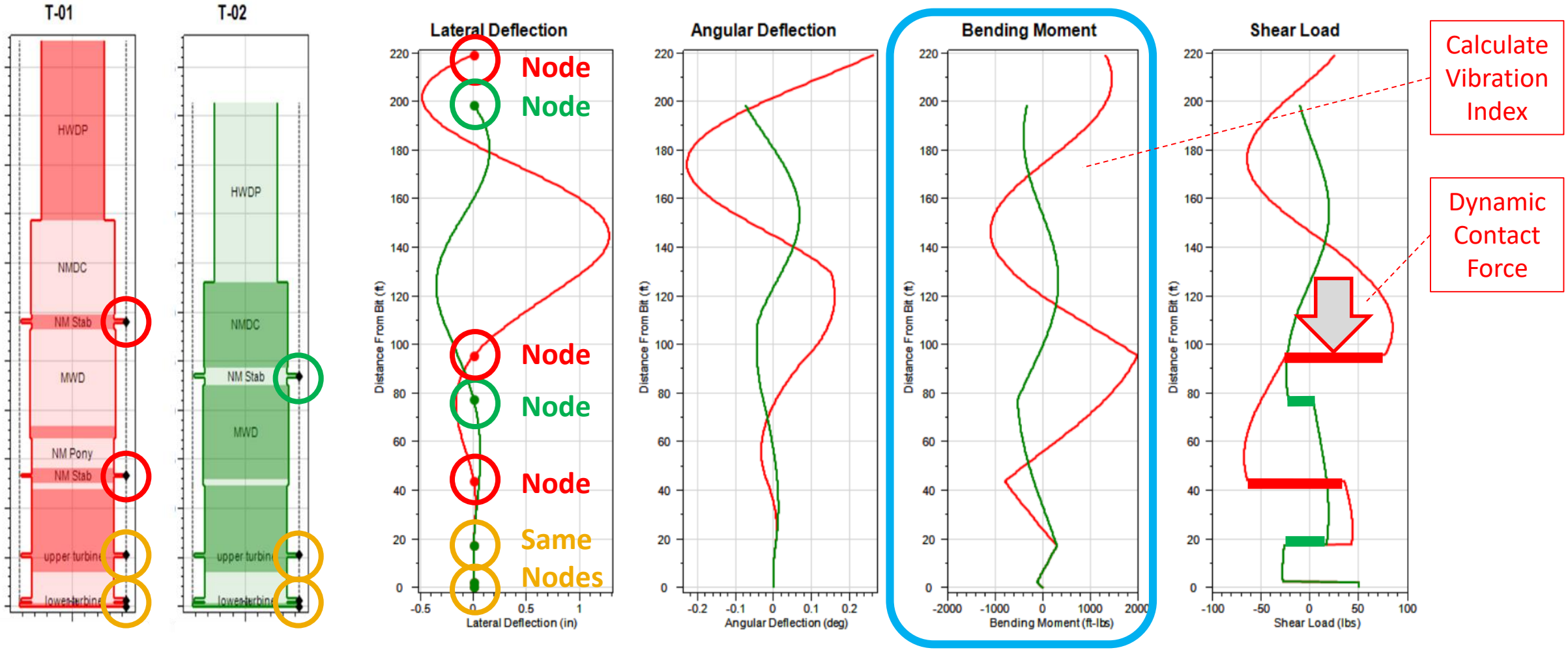


Shear Load



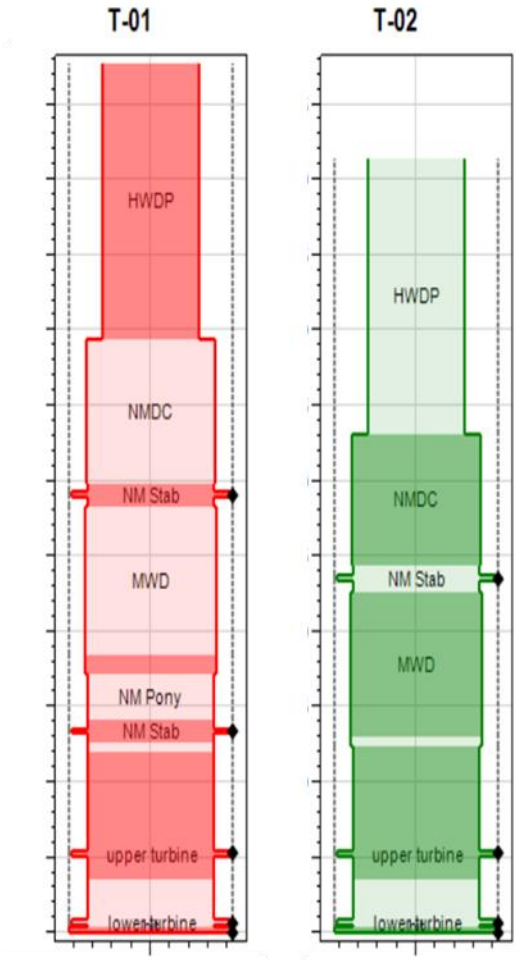
Calculate States for Each RPM and WOB Value

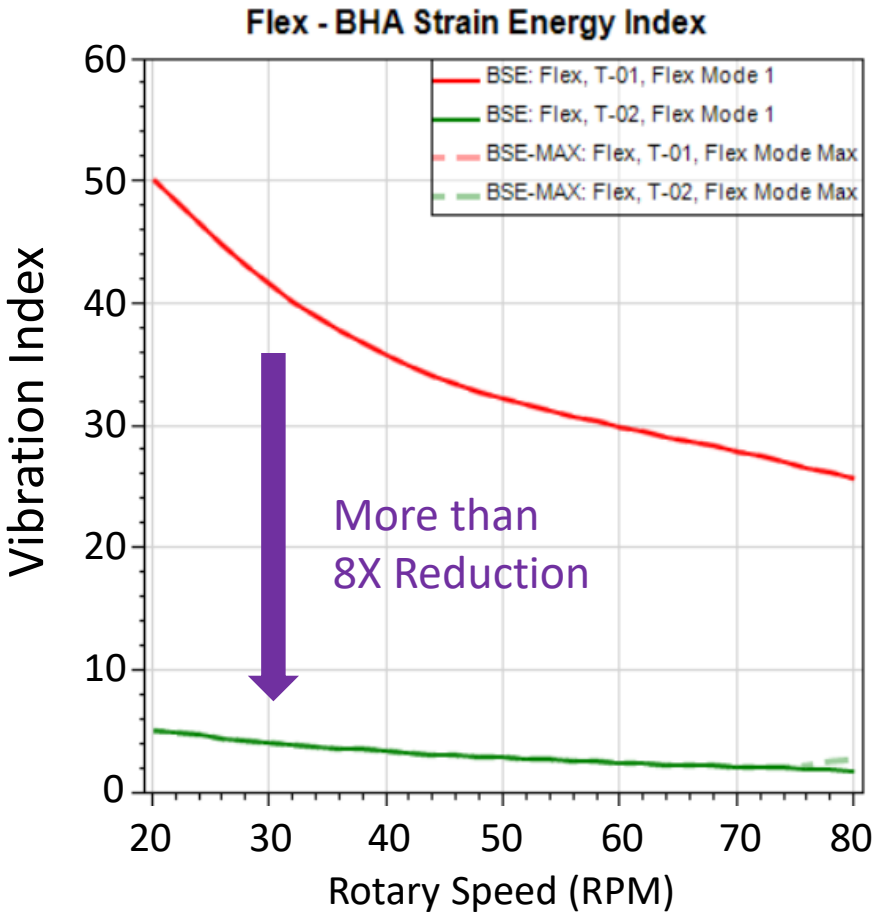
- Two BHAs, turbine with diamond impreg bit, dynamic states at 30 RPM & 20 klbs WOB
- Location of Red nodes creates **disruptive pattern** relative to Green nodes



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

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Relatively simple modeling process

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

Rakusen/87397566/Getty Images

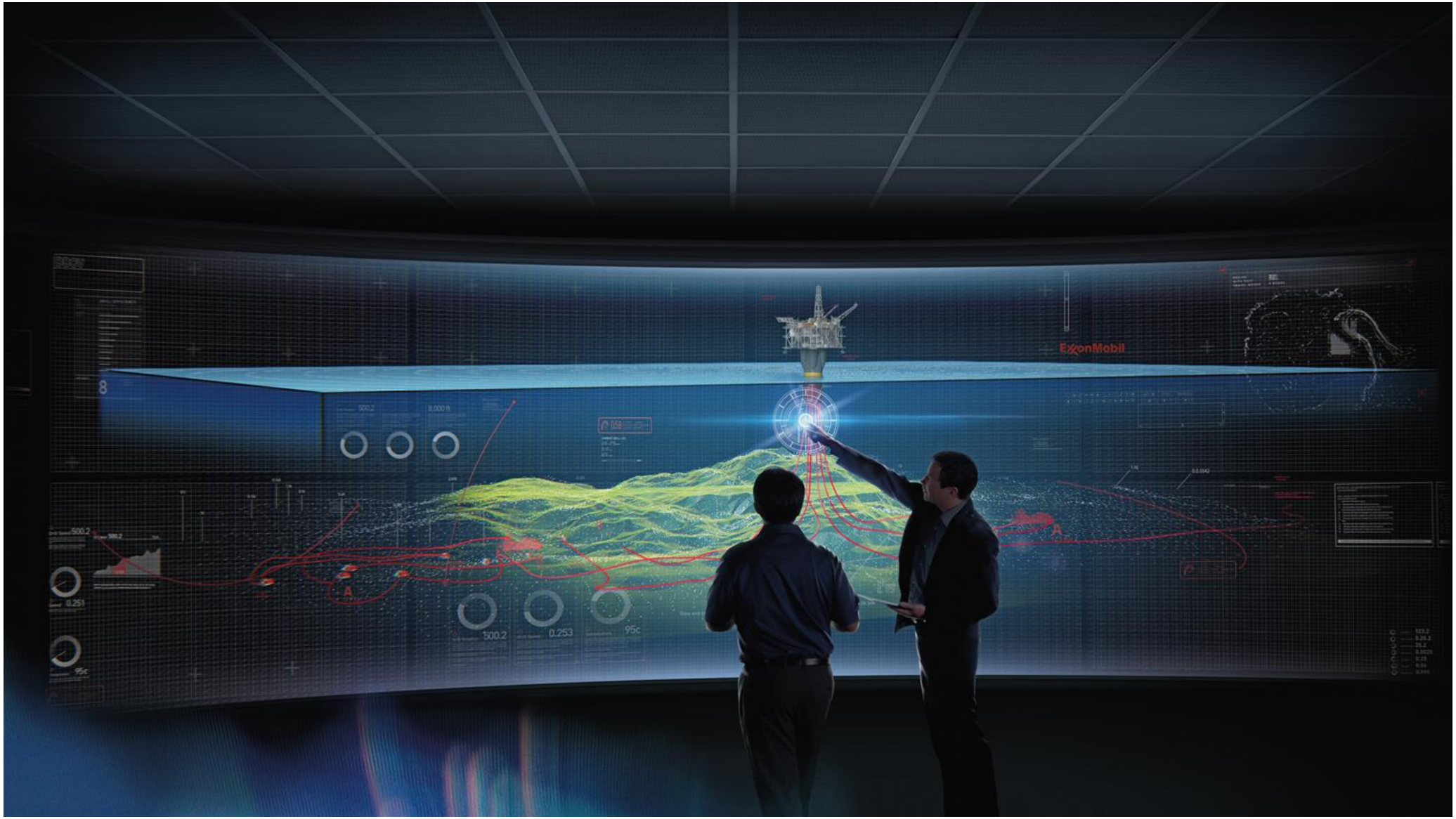
“Forced Frequency Response”

- 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

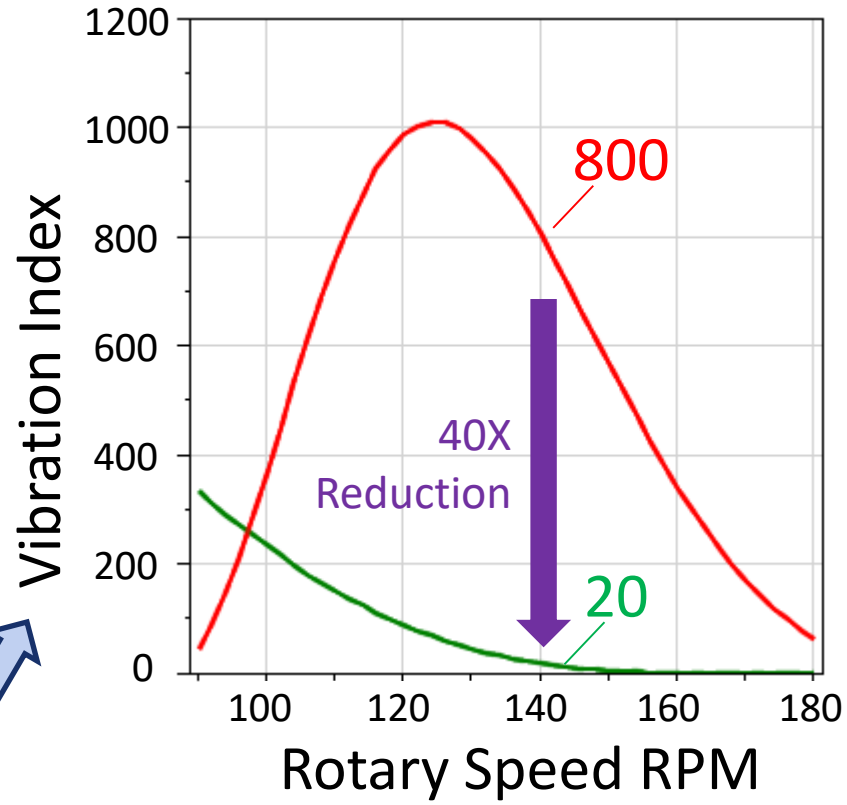
- Identify sweet spots and potential resonance risk
- Model results independent of geology, formations, drilling fluid, etc.
- Expect differences in drilling depending on conditions

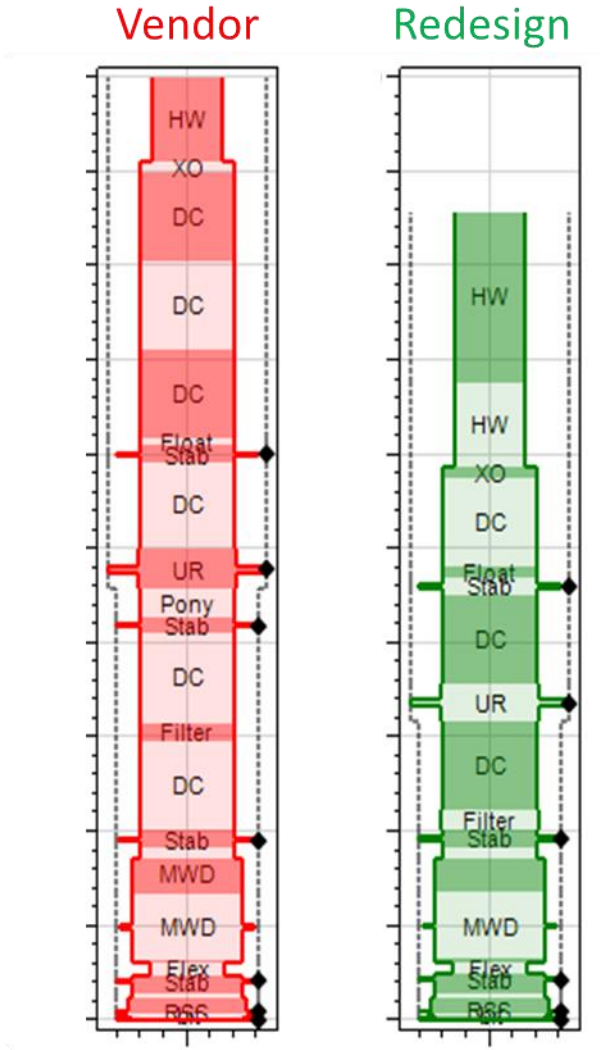
Application Case Studies



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



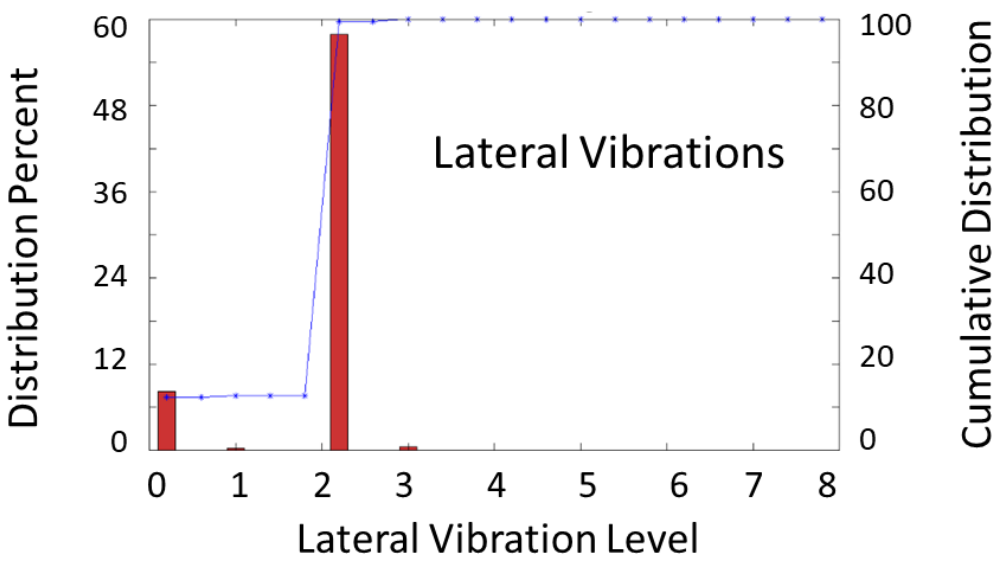


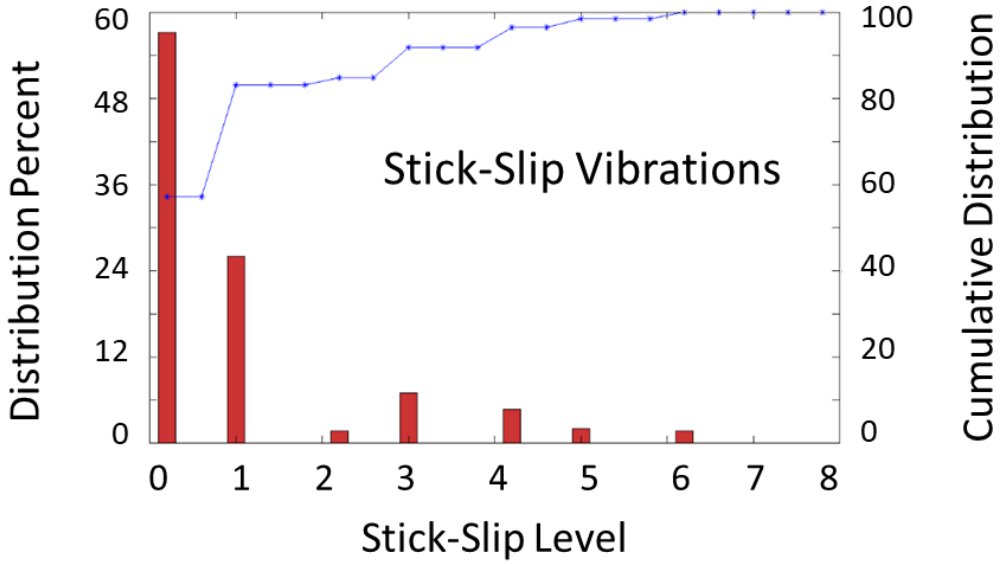
"Vibration Index" ~ Bending Strain Energy Averaged along the BHA length

Good Drilling and Low Vibrations

Maintained WOB (24 klbs avg.) in soft formation at 88° hole angle

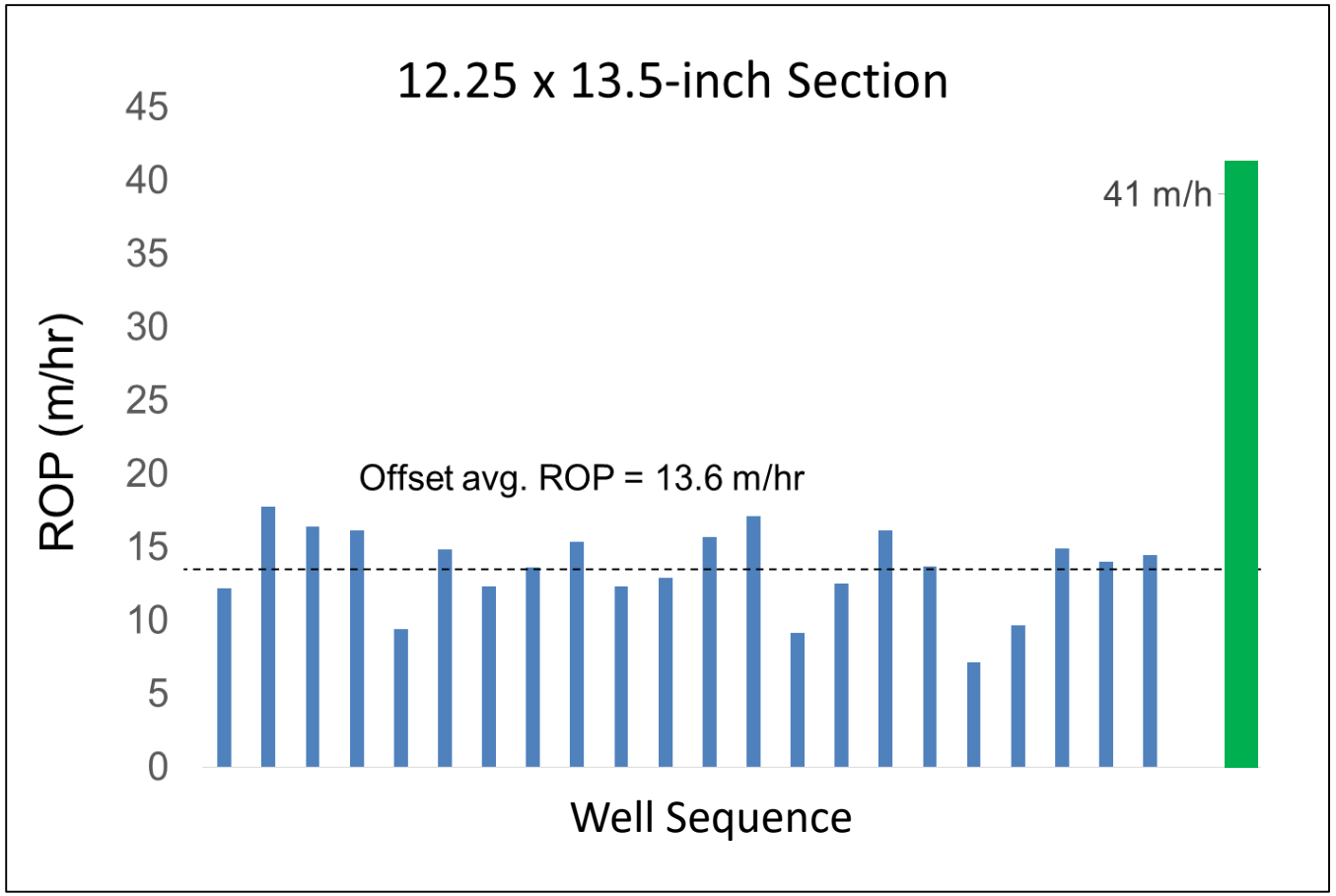
- 130 RPM (model sweet spot)
- 41 m/hr average drilling ROP
  - 69 m/hr instantaneous ROP
- Lateral vibrations < 2g RMS
- Low stick-slip, severity average < 1
  - Sticking ratio less than 0.4
- Zero axial vibrations





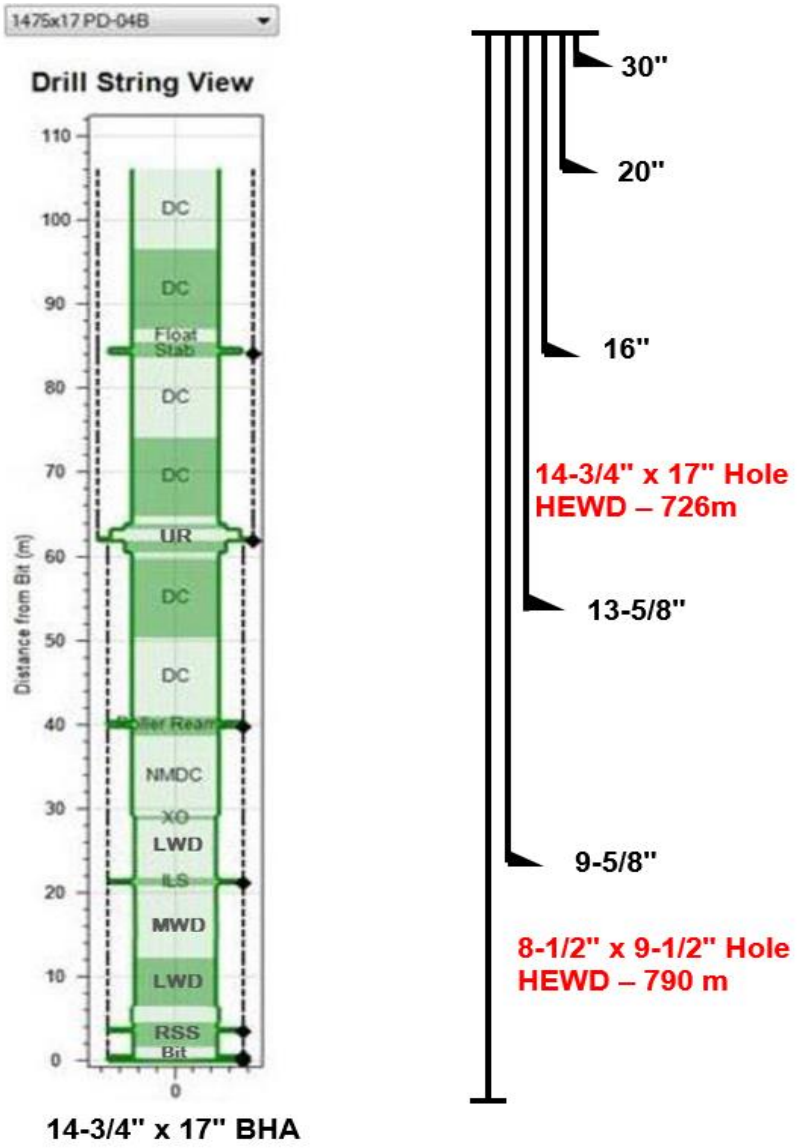
Steady "Making Hole" & Exemplary Performance

3X ROP vs. Average of 21 Prior Offsets



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



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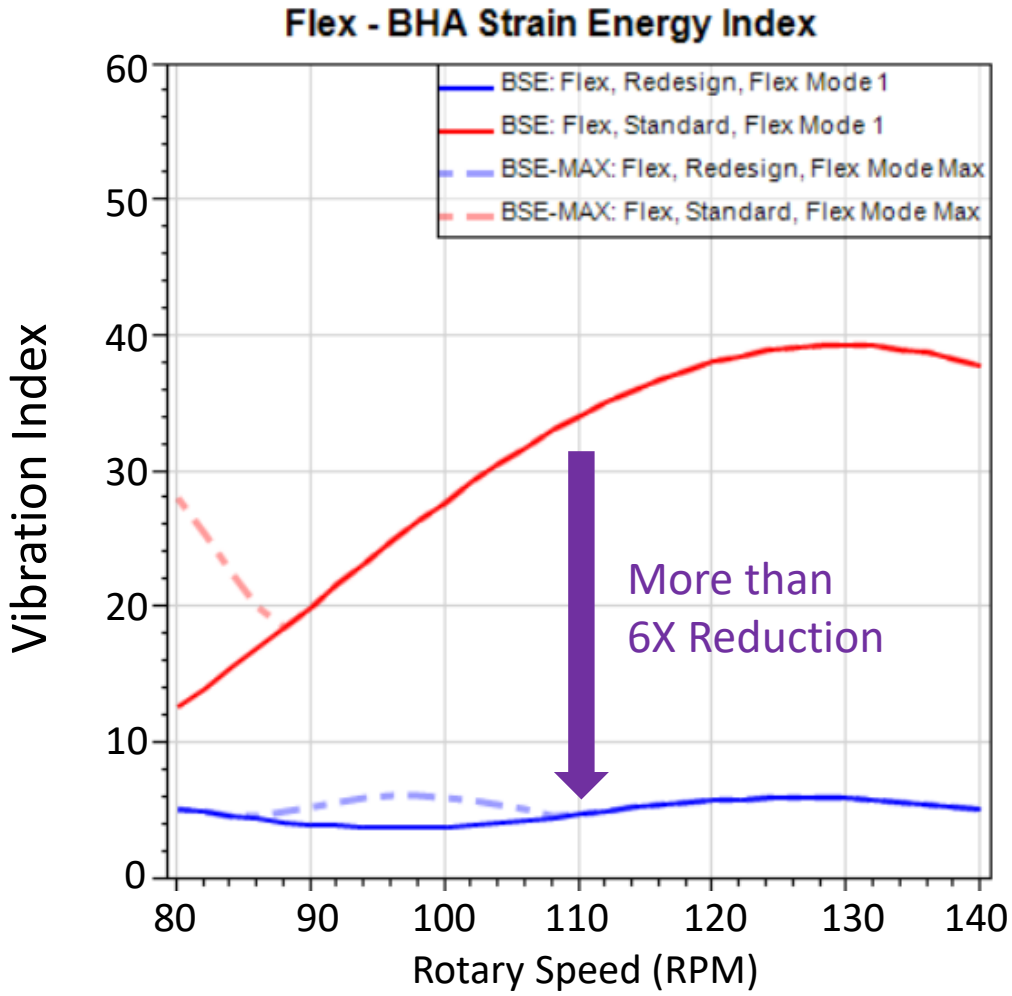
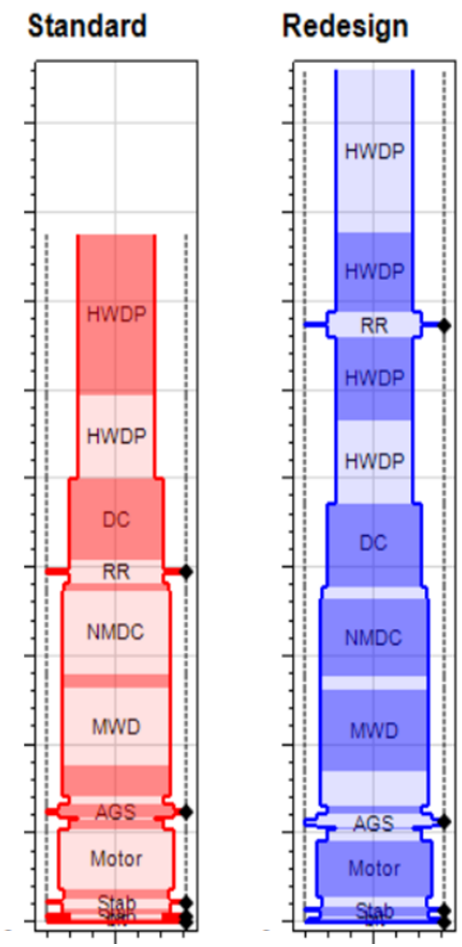
Case No. 2: Motor BHA Design

Two design changes:

- Remove contact below motor
- Move roller reamer above two joints of heavyweight pipe

Redesigned BHA vibration indices lower than Standard BHA



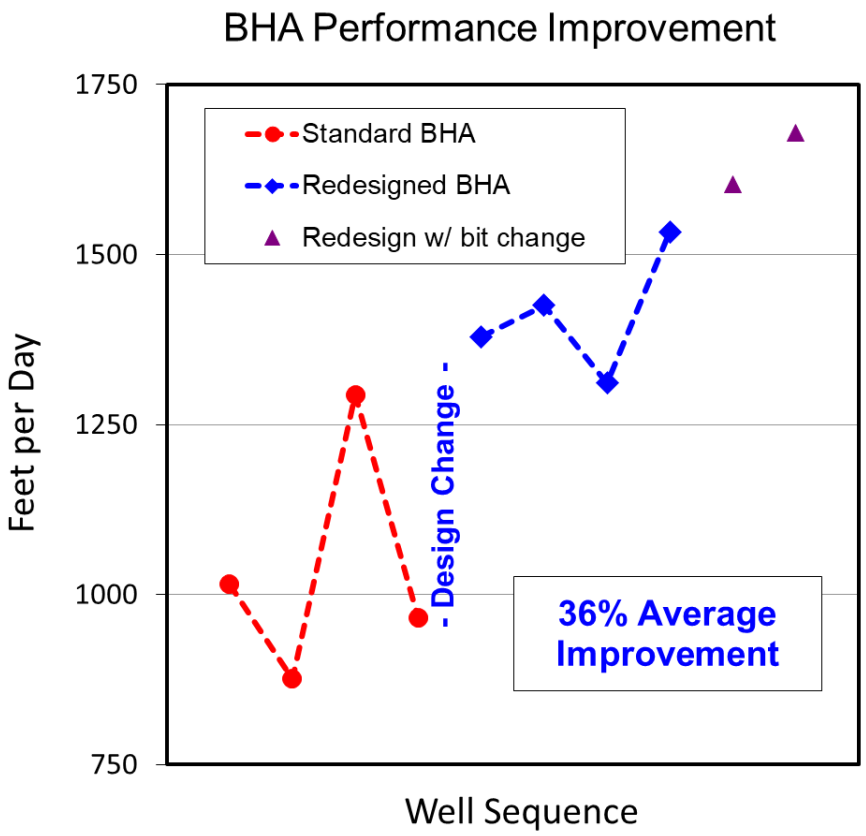


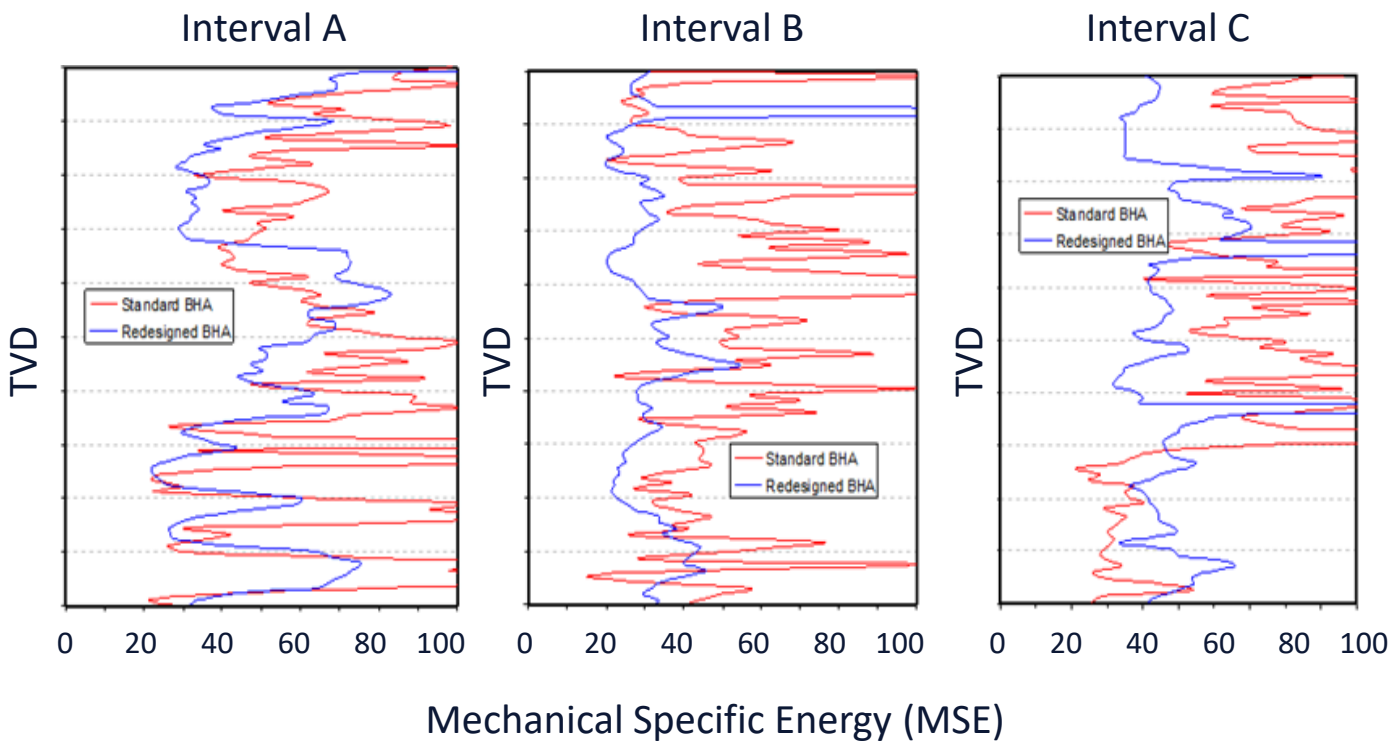
Faster Cycle Time, Better Performance

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

Redesigned BHA reduces MSE < 100 ksi

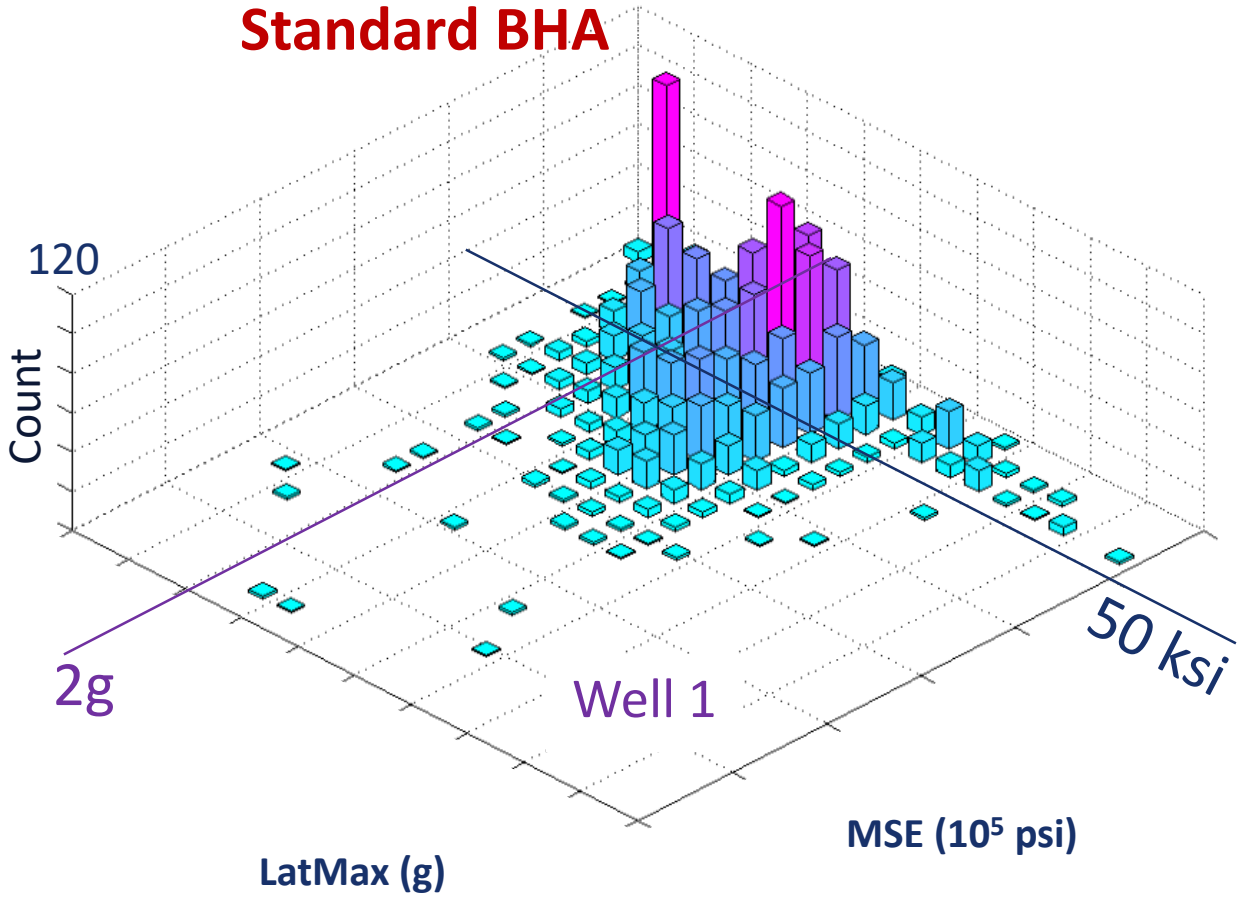
- Mechanical Specific Energy (MSE) measures the amount of work expended to drill rock

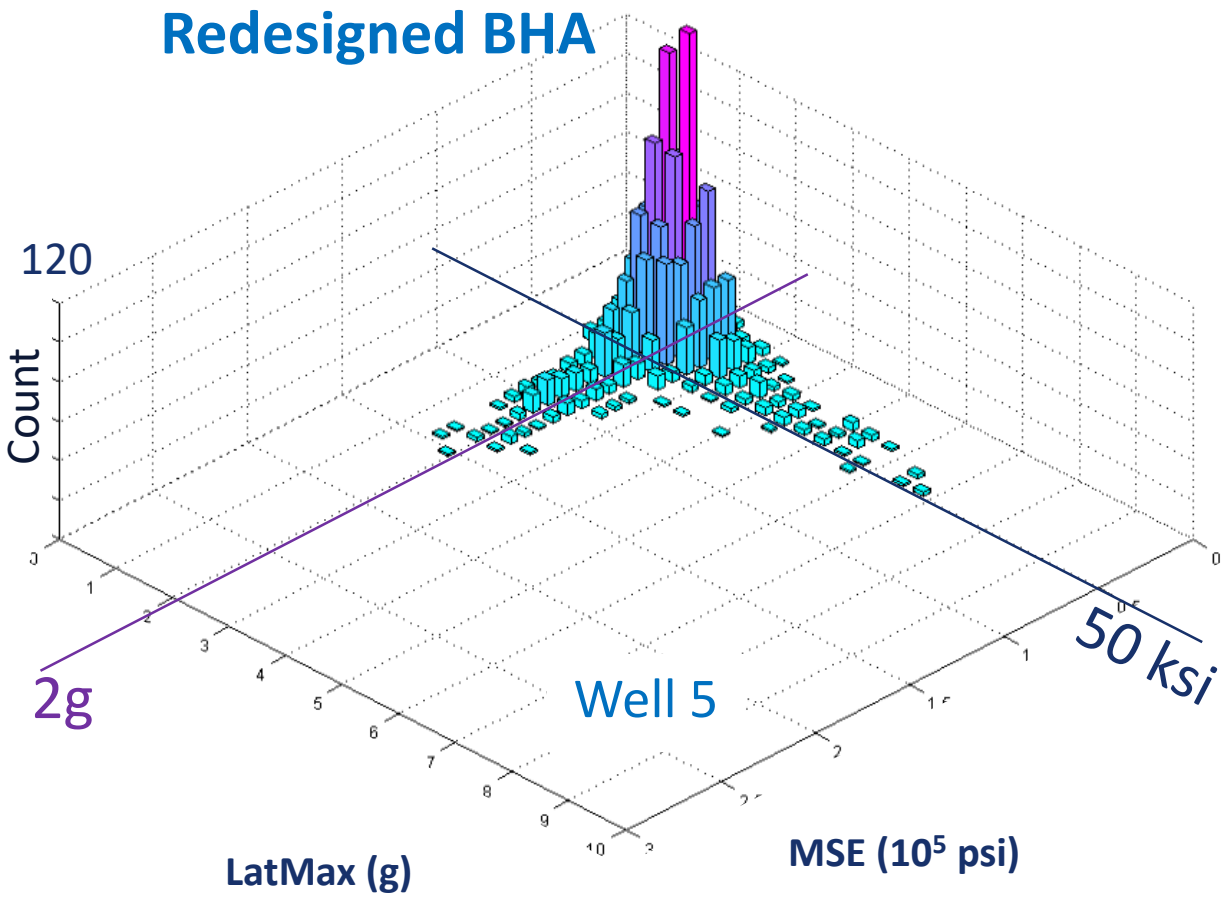




Lateral Vibration and MSE Data

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





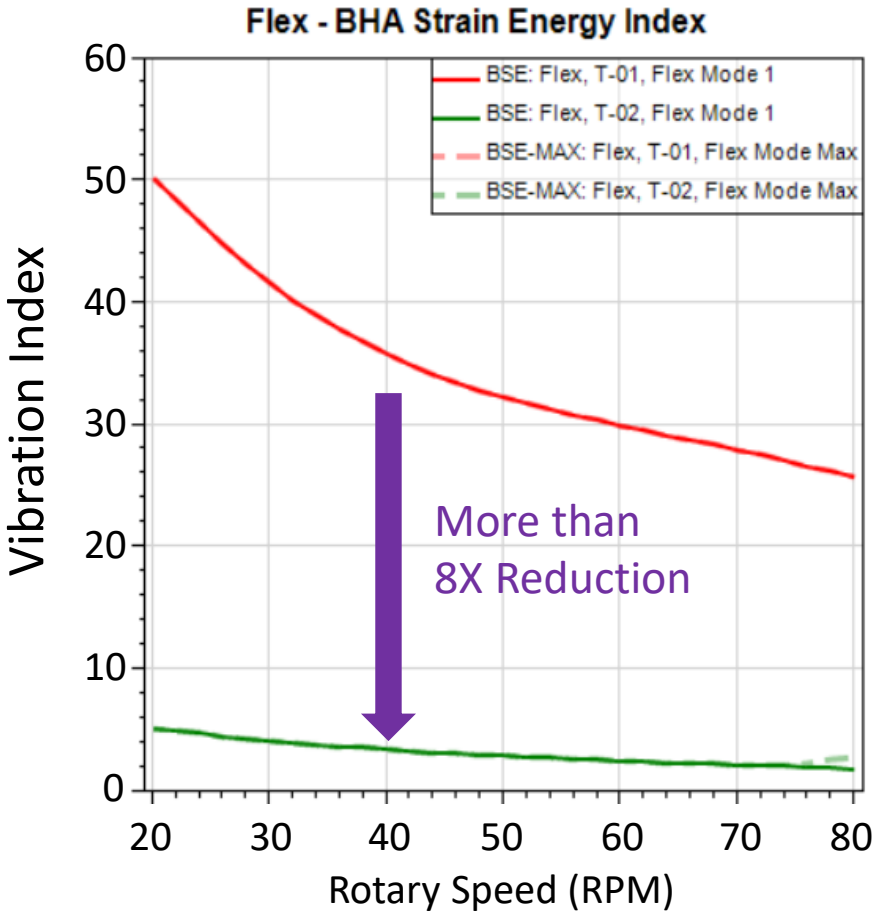
Case No. 3: Turbine BHA / Diamond Impreg Bit

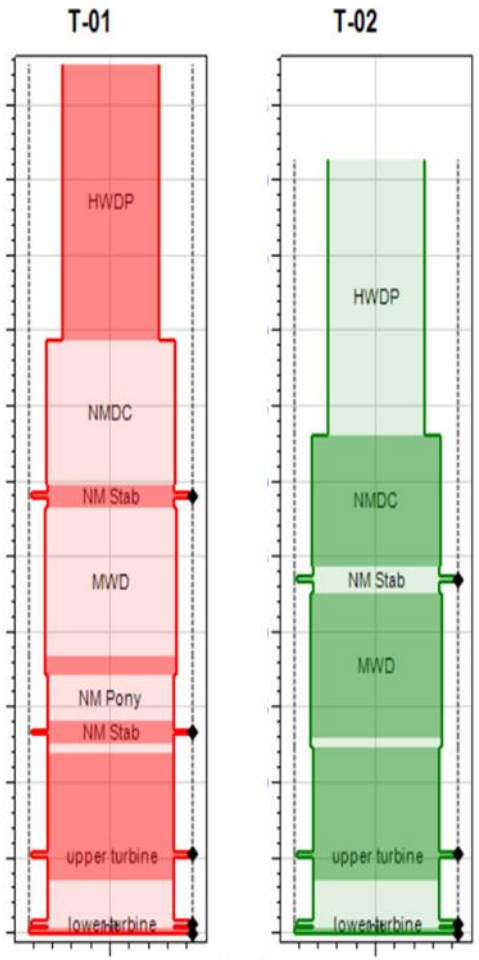
T-01 design for three runs

- 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

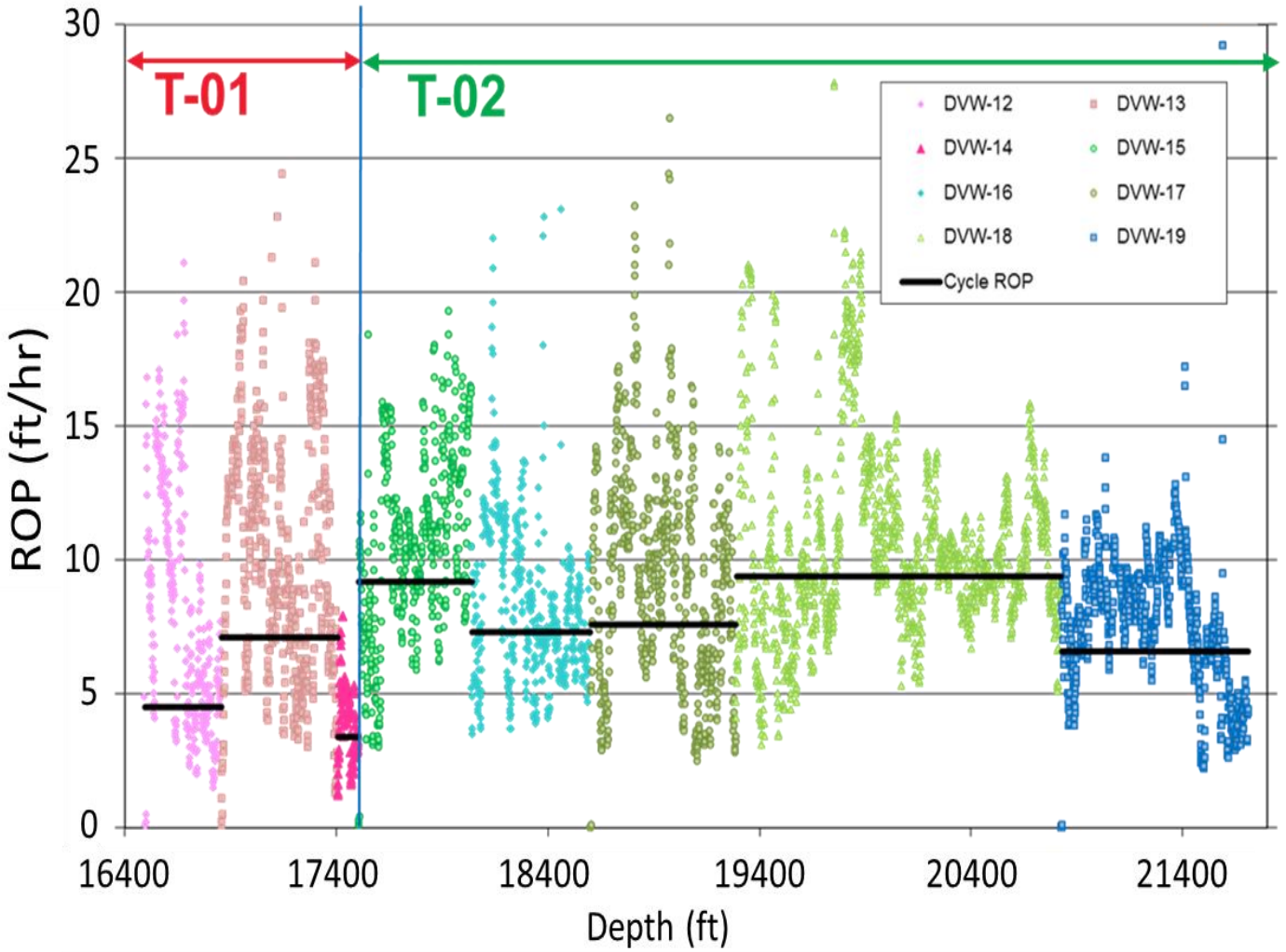




Better Drilling Results with Optimized BHA

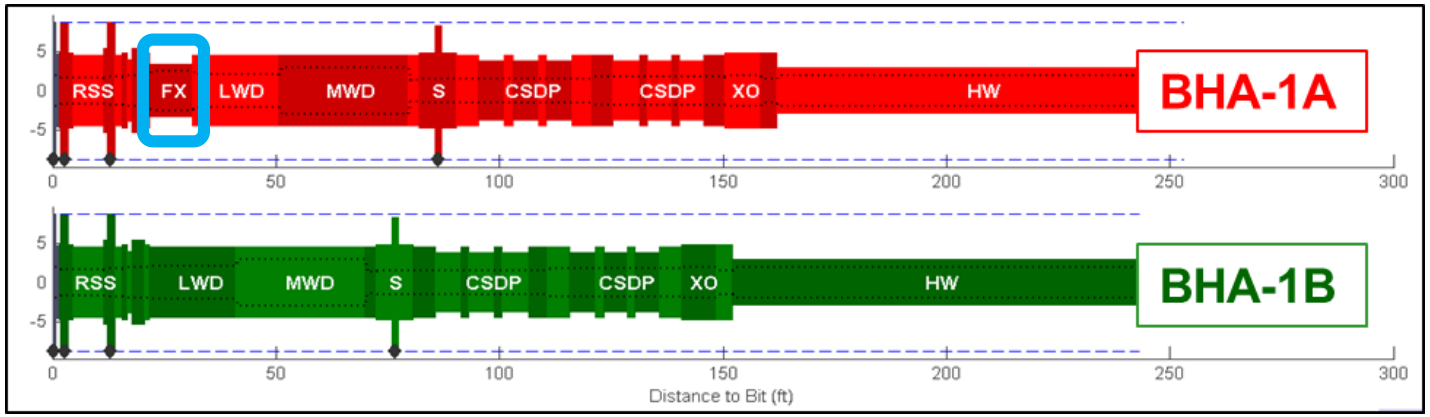
- ROP Increased 60%
- Run Hours Up 68%
- Interval Length Up 150%
- MSE Decreased 30%

Bit Grades	
T-01	T-02
1-1-WT	7-8-NR
2-4-WT	4-4-NR
1-1-WT	8-8-CR
	5-5-WT
	3-3-WT



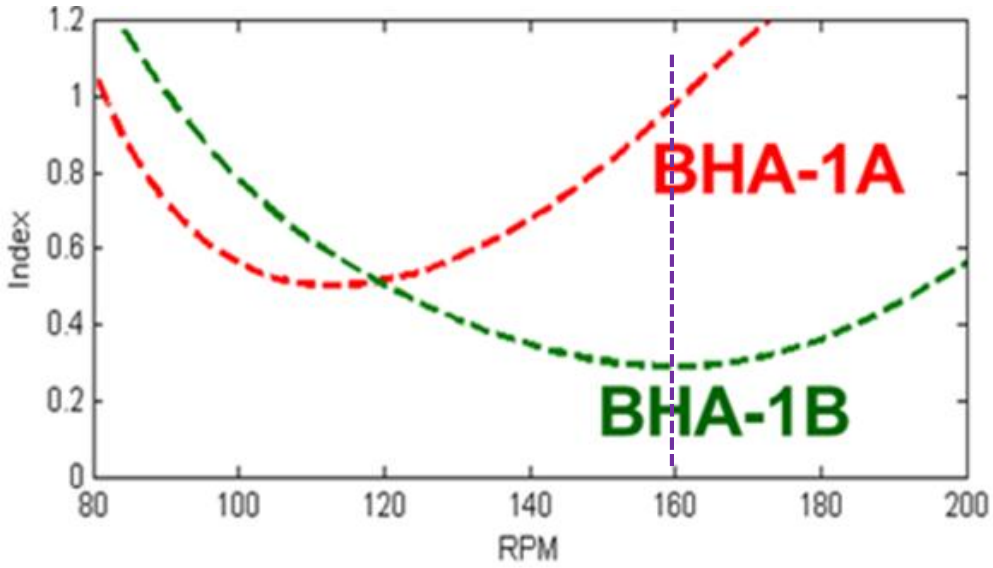
Case No. 4 Rotary Steerable BHA Redesign

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



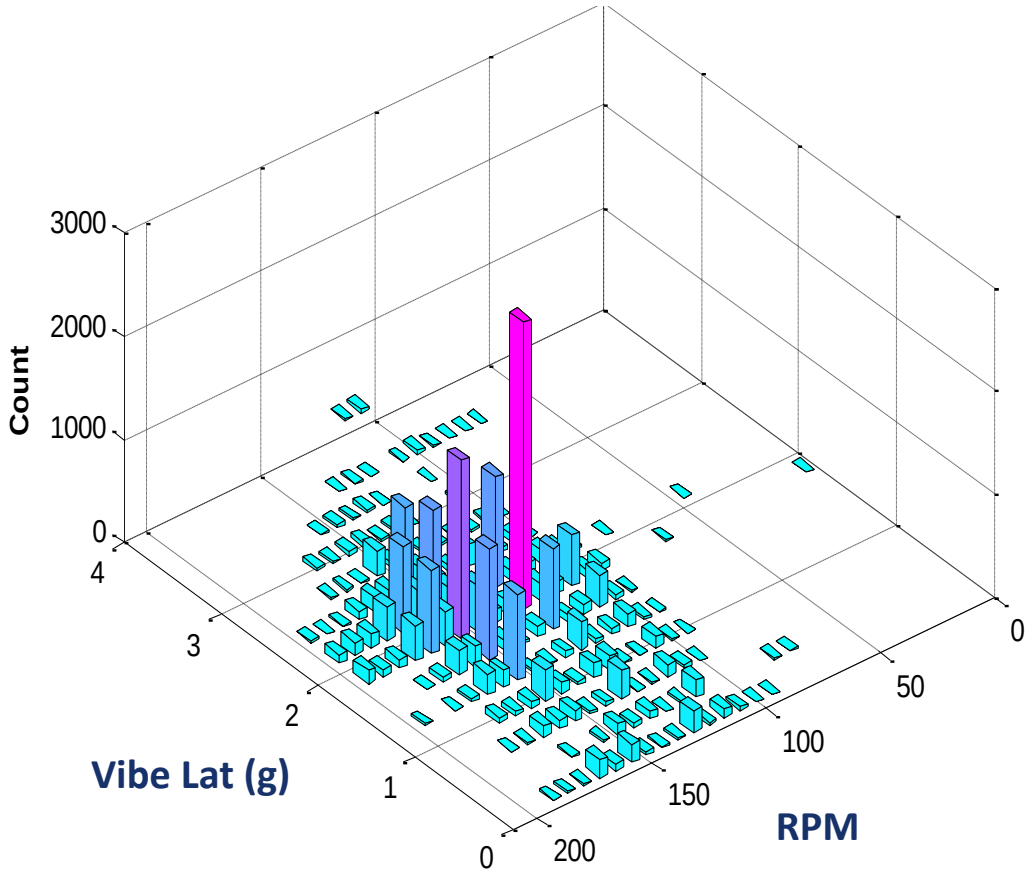
Schematics of BHA Designs

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

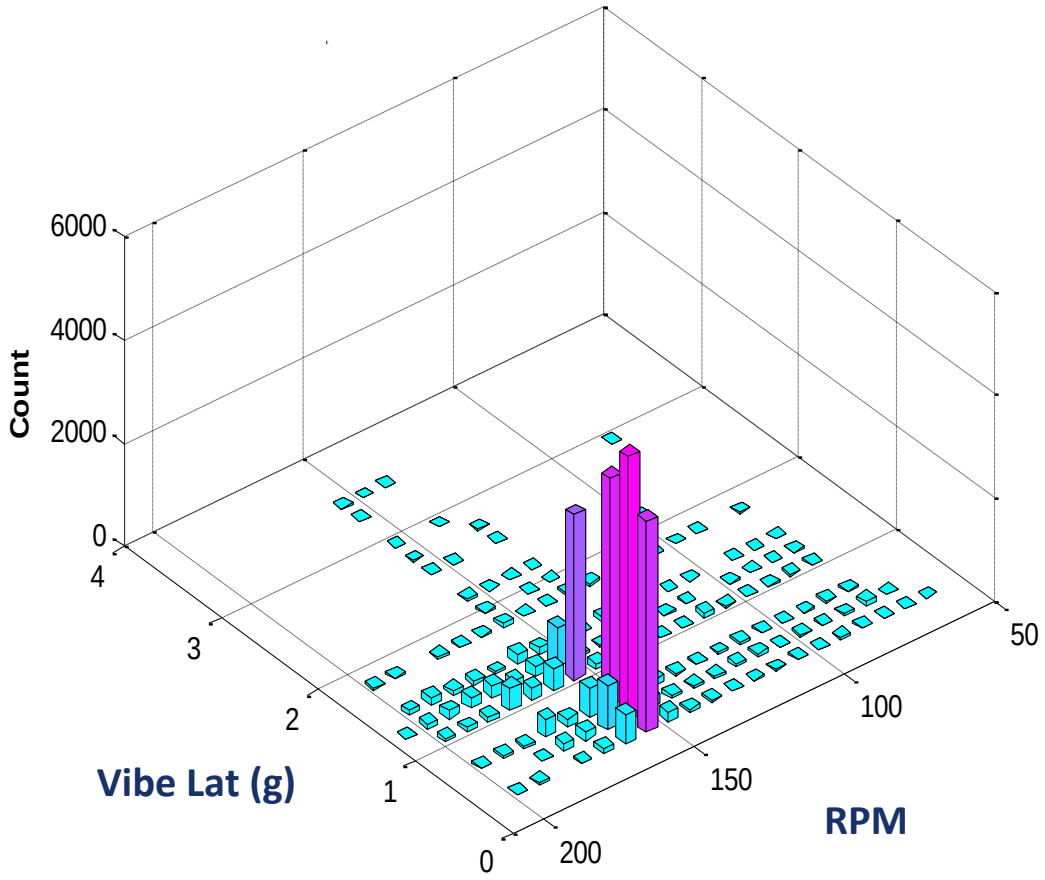


Population Distribution of Lateral Vibrations

BHA-1A average: 1.8 g



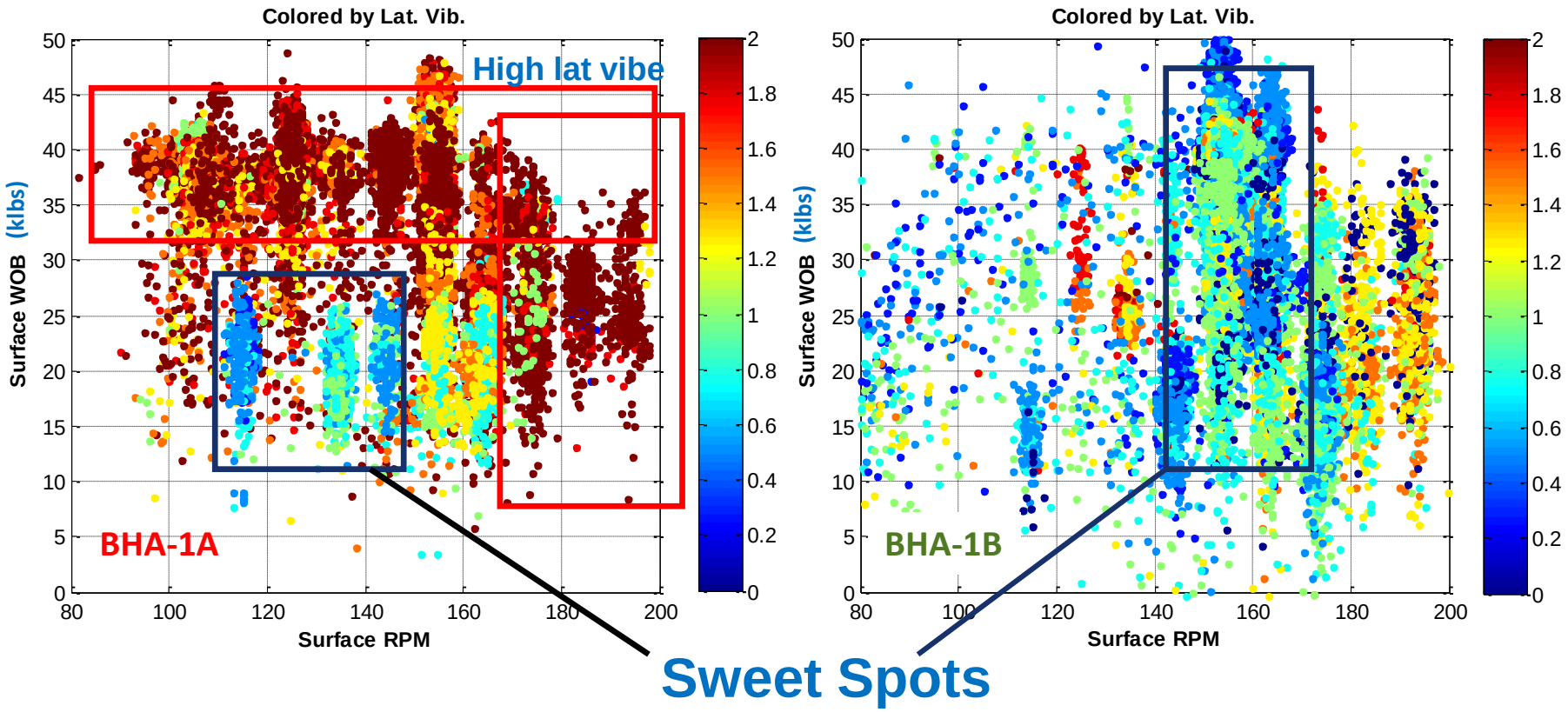
BHA-1B average: 0.6 g



Comparison of Measured Data

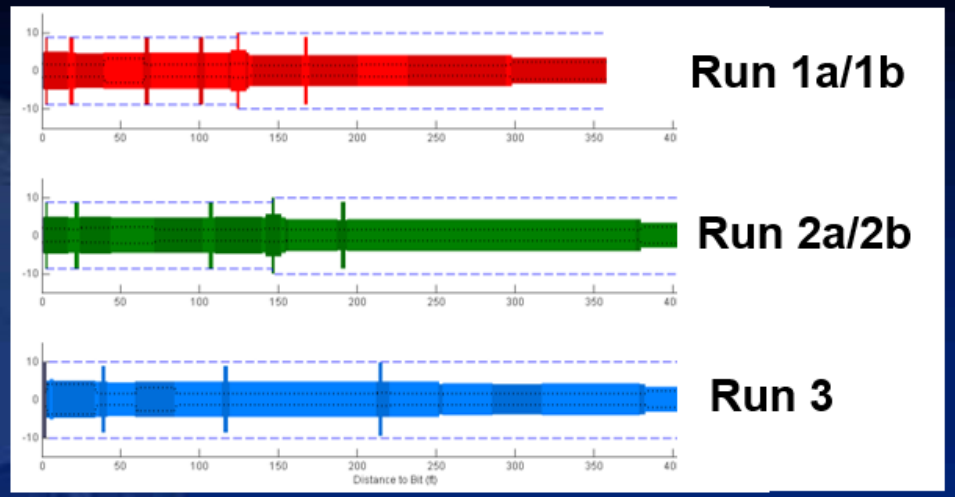
Lateral Vibration Measurements vs. RPM and WOB

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

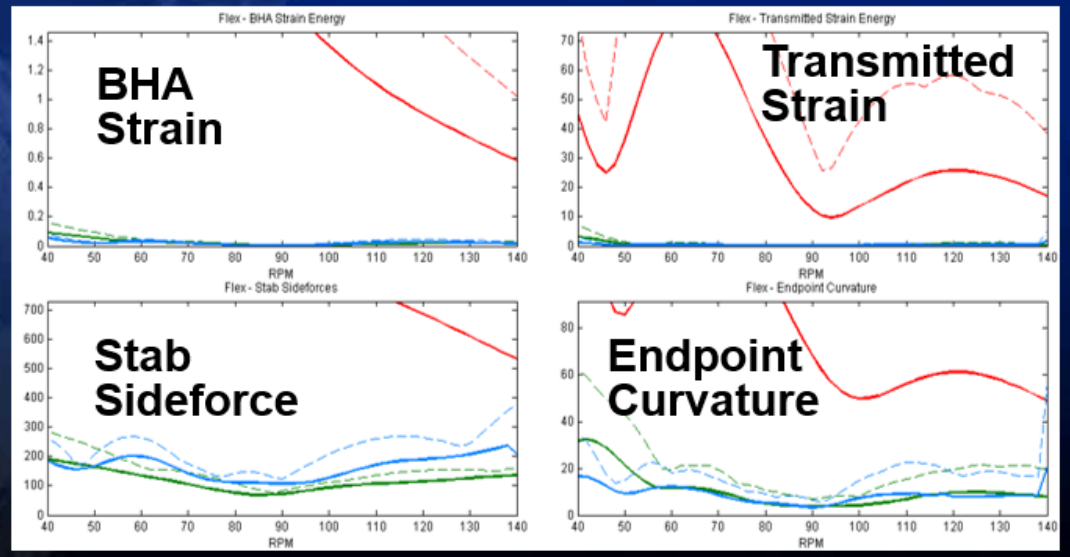


Case No. 5 BHA Design Affects Borehole Quality

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



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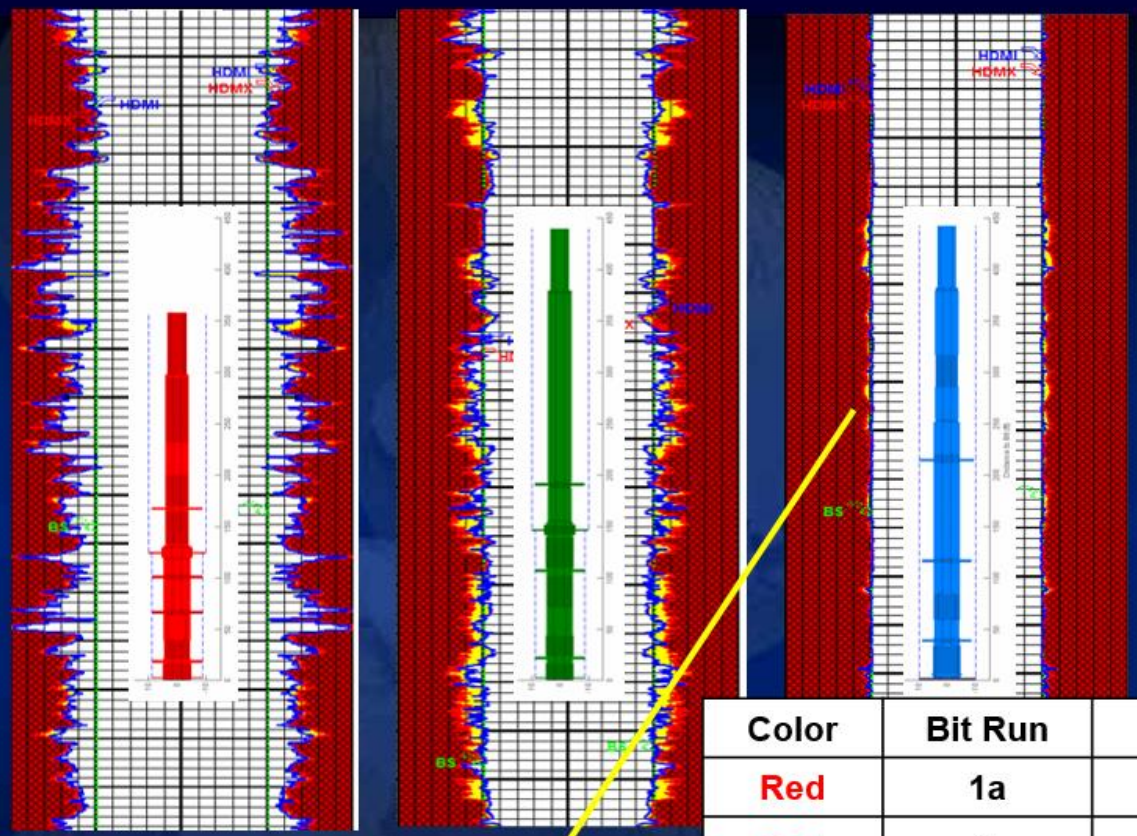
Case No. 5 BHA Design Affects Borehole Quality



Result - strong correlation of borehole enlargement with indices

(Note that interval was drilled with NAF fluid)

Extremely stable BHA and Bi-Center bit run; Gauge hole

Color	Bit Run	Footage	ROP
Red	1a	813 ft	45.2 ft/hr
Red	1b	914 ft	43.5 ft/hr
Green	2a	1094 ft	25.0 ft/hr
Green	2b	1164 ft	25.3 ft/hr
Blue	3	2486 ft	21.8 ft/hr

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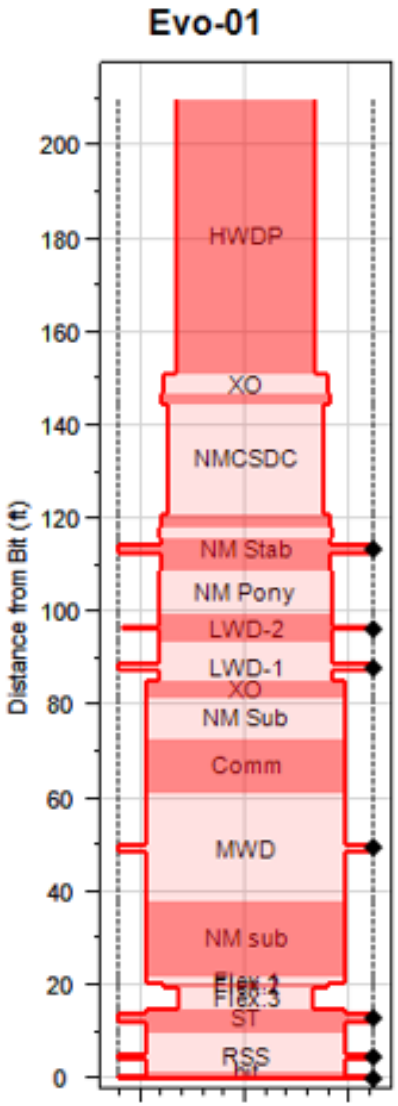
Case No. 6 Step-by-Step Guide to Lower Indices

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?



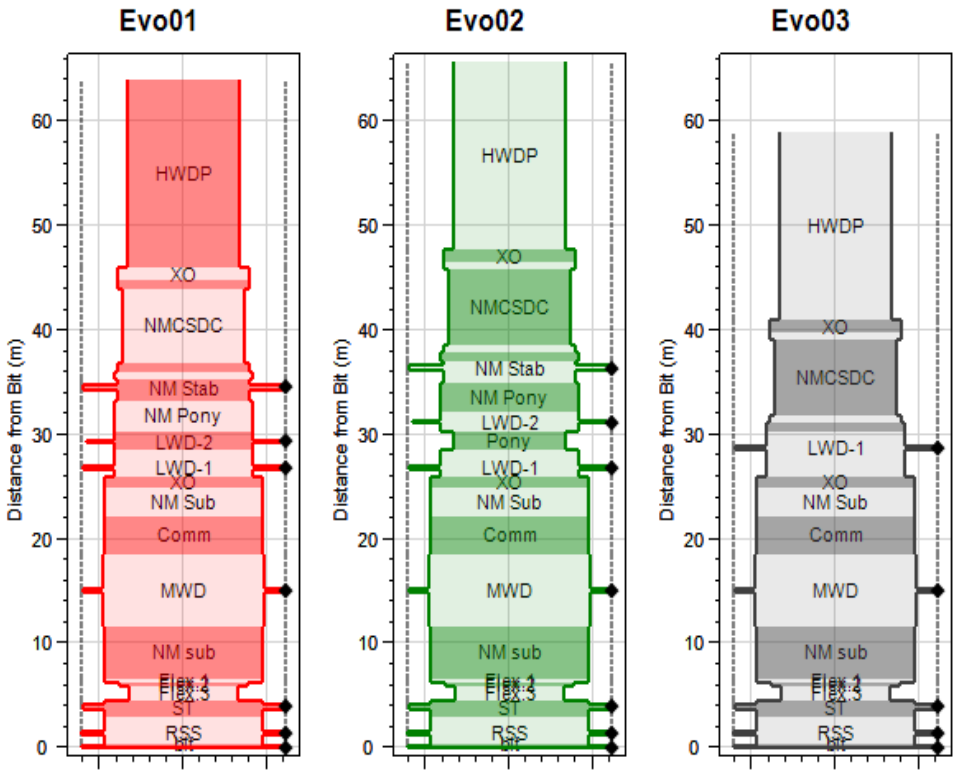
Step 1: Combine or Separate Contacts

Preferred approach: Combine LWD1 and LWD2

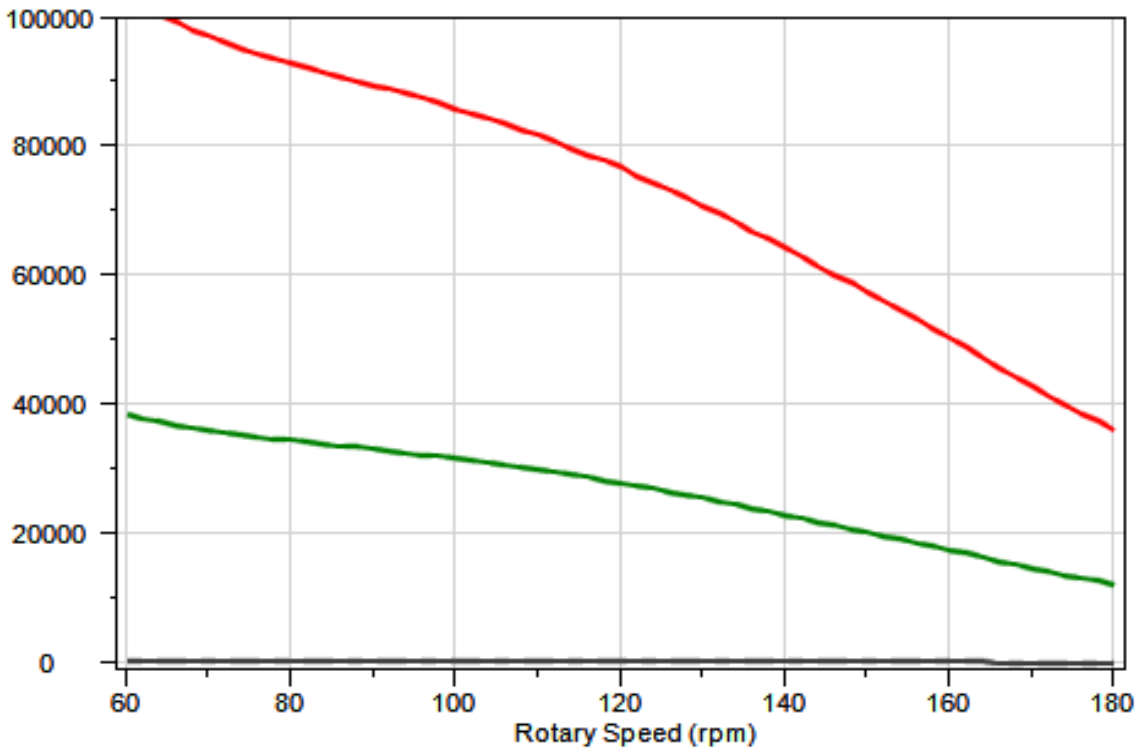
Alternate approach: Spacer between LWD1 & LWD2

Combination of tools is best

LWD1 and LWD2 Spacing



Significant Reduction in Index Values



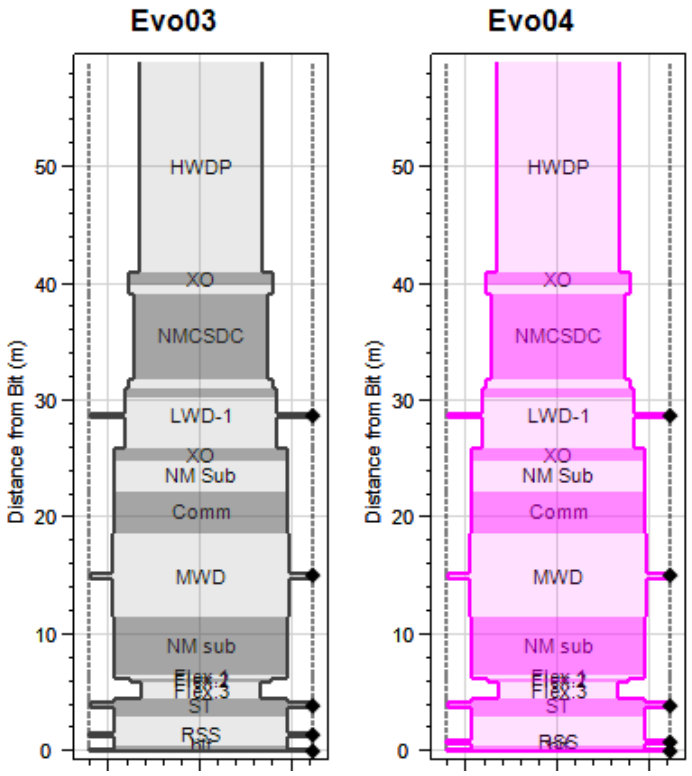
Step 2: Reduce Distance to Near Bit Support

Move near bit support closer to bit

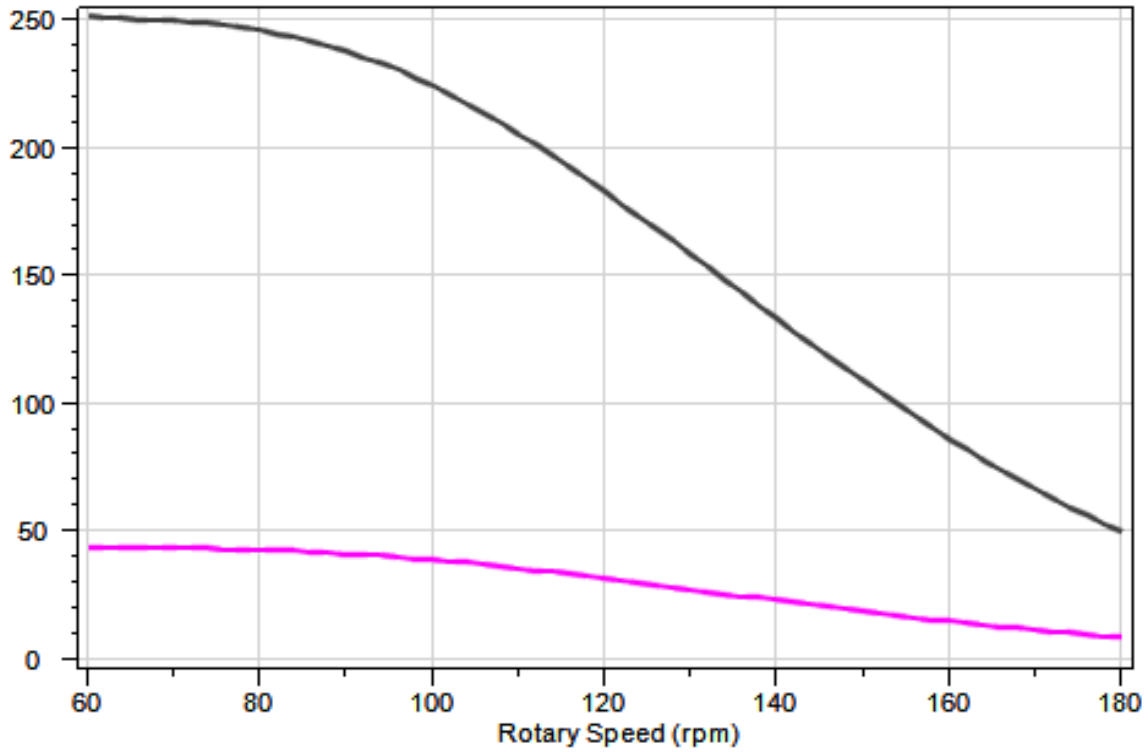
- Similar in concept to seeking long gauge bit

Close contact to bit is good

Closer Nearbit Contact



More Reduction



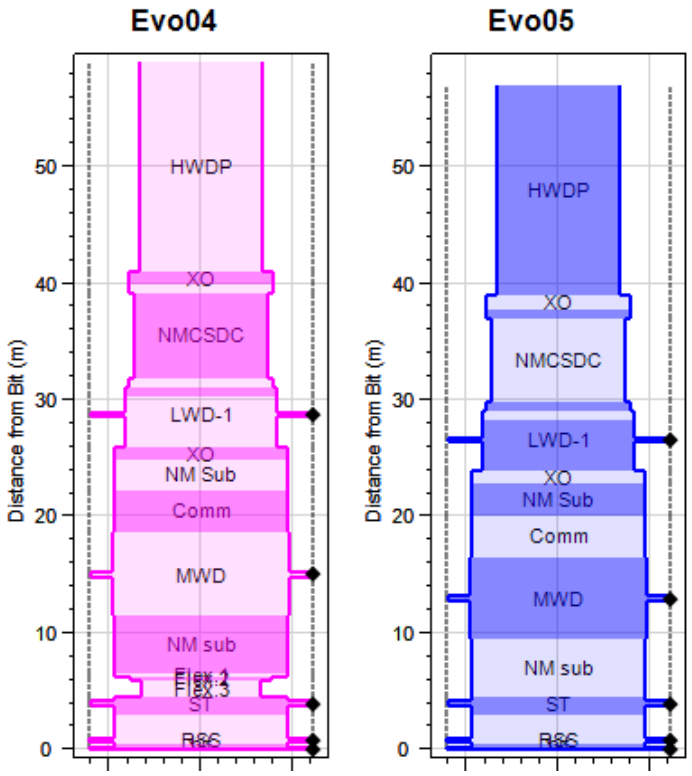
Step 3: Increase Near Bit Stability

Remove Flex Sub below fourth contact point

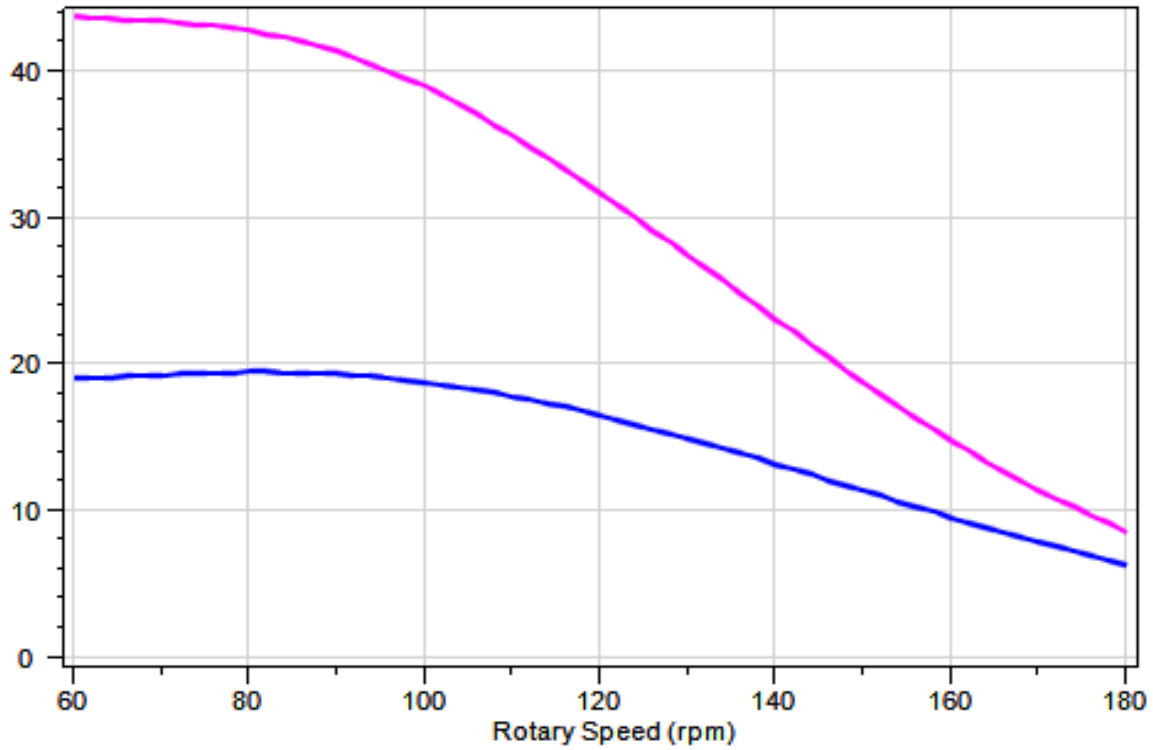
- Stiffness up to 4th contact governs lateral stability

Not always feasible with current tools

Increase Nearbit Stiffness



Significant Additional Reduction



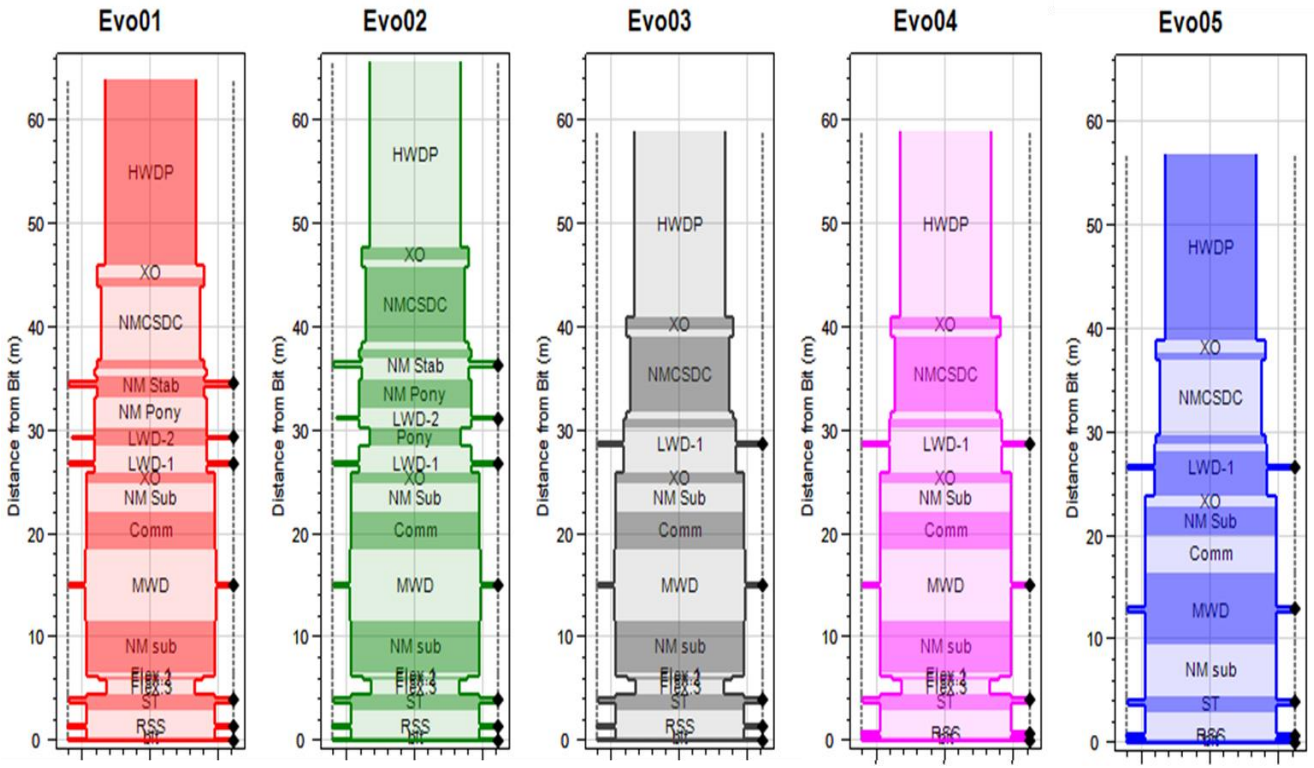
Step-by-Step Guide to Lower Vibration Indices

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

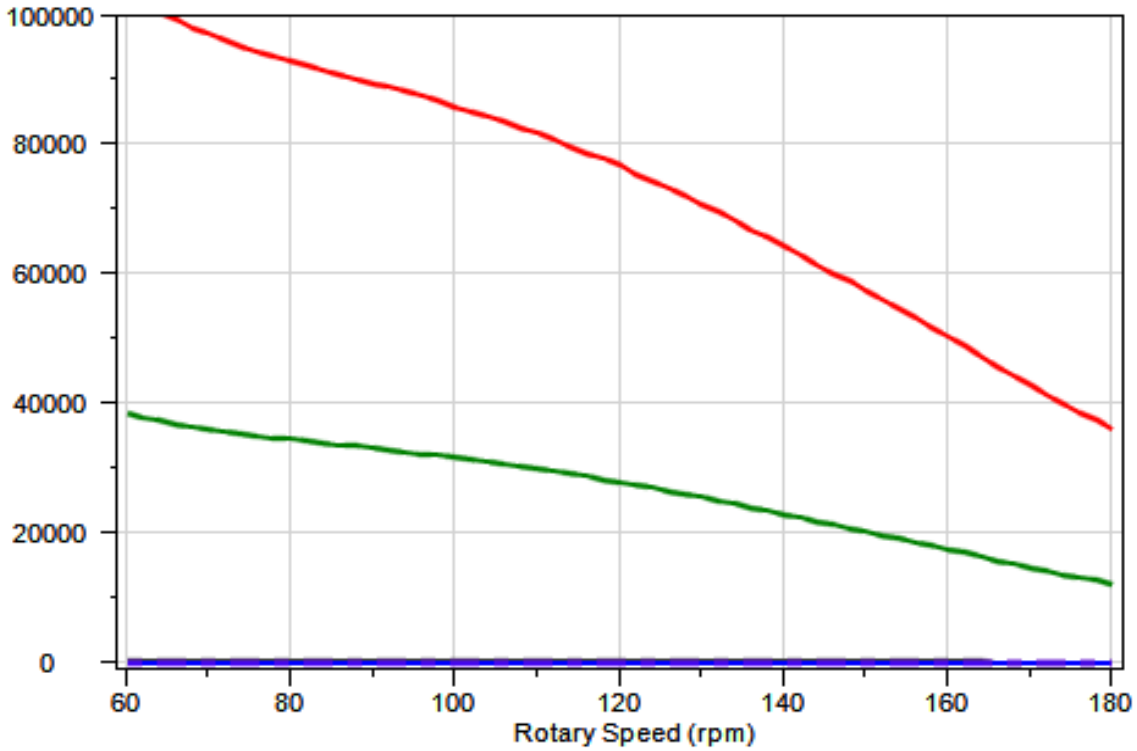
Field results confirm what model is telling us

Combined effects

LWD Spacing, Closer Nearbit Contact, No Flex



Huge Reduction in Index Values



SPE 163503 • Design Evolution of Drilling Tools to Mitigate Vibrations

Data Required for Analysis

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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

artisteer/846462204/Getty Images

How do we get this technology in every foot of hole we drill?

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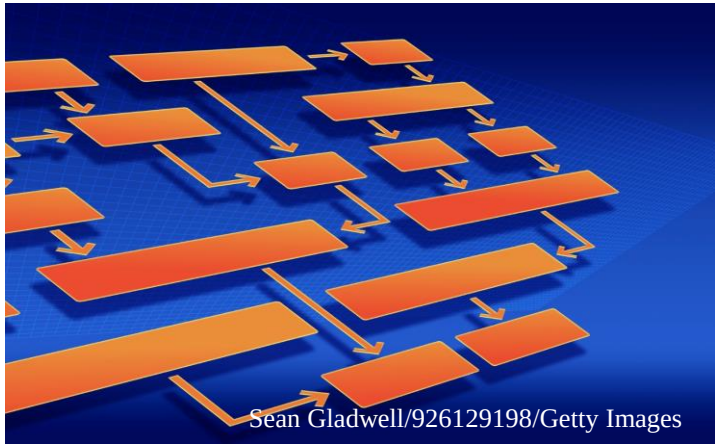
It's All About The Workflow!



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

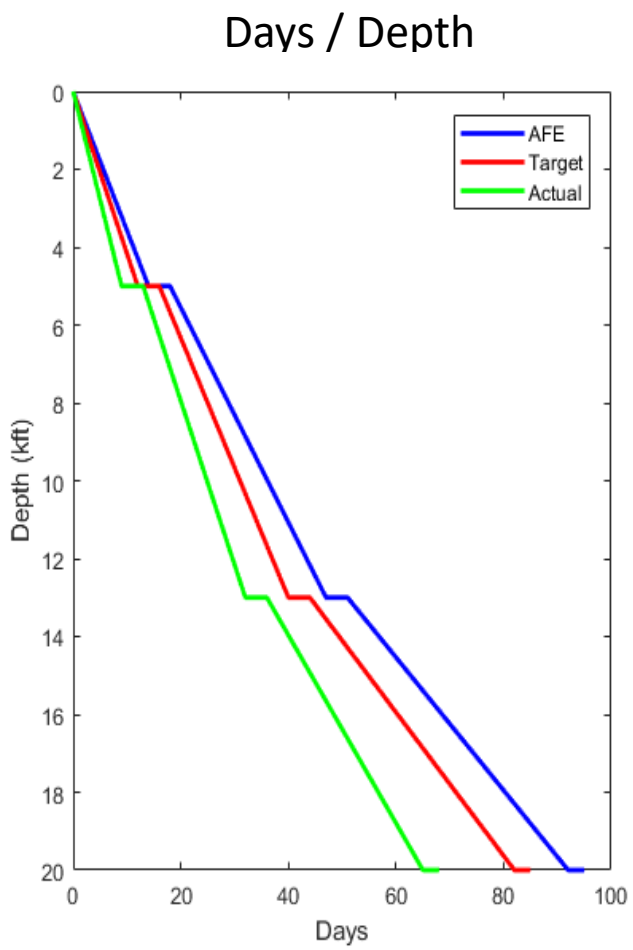
SPE/IADC 163503 • Design Evolution of Drilling Tools to Mitigate Vibrations

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?

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