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PDC Bit Design Optimization and Applications

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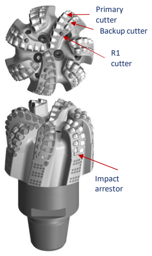
Dr. Chen is a chief technical advisor at Halliburton Drill Bits and Services. He has been with Halliburton for 22 years specializing bit (roller cone bits and PDC bits) design optimization and simulation. He has authored and co-authored more than 20 technical papers and holds 38 US patents. He holds a Ph.D. degree in mechanical engineering from University of Liege, Belgium.

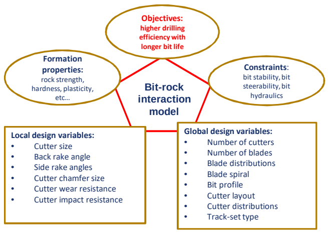
Dr. Shilin Chen

Typical PDC Bit Design

- Many elements comprise current modern PDC bits: primary cutters, backup cutters, R1 cutters, and depth of cut (DOC) controllers, such as impact arrestors.
- Although these elements play different roles in drilling, they all have **one common goal: drilling faster and longer** by meeting other requirements, such as steerability and stability.
- To meet these requirements, the locations and orientations of these elements on the bit body should be optimally designed.



PDC Bit Design Optimization



The **bit-rock interaction model** is a key element for optimization.

Polycrystalline Diamond Compact (PDC) Bit Design Optimization and Applications

Part 1: New Bit-Rock Interaction Model
- New Cutter Force Model
- Rock Chip Model
- Cutter Wear Consideration
- Model Validation

Part 2: New Layout Method for Primary Cutters to Improve Drilling Efficiency
- Force-Balanced (FB) Cutter Groups
- Design Examples
- Laboratory and Field Validation

Part 3: New Layout Method for Backup Cutters to Extend Bit Life Without Affecting Rate of Penetration (ROP)
- Depth of cut at bit level and at cutter level
- Critical Depth of Cut
- Active and Passive Backup Cutters
- Design Examples and Field Applications

Part 1: New Bit-Rock Interaction Model

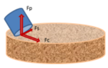
- The Problems of Area Based Cutter Force Model
- New Cutter Force Model
- Rock Chip Model
- Cutter Wear Consideration
- Model Validation

Traditional Cutter Force Model: Area-Based Model

Based on the definition of specific energy,

$$SE = \frac{Energy}{Volume\ Removed} = \frac{F_c\ d}{A\ d} = \frac{F_c}{A}$$

if: $SE \propto \sigma$,
then: $\boldsymbol{F_c = k_c \sigma A}$



Almost all published single-cutter force models have the following form (Glowka, Behr, Warren, Detournay):

$F_c = f_c(\alpha,\beta,\mu)\ \sigma\ A$; $F_p = f_p(\alpha,\beta,\mu)\ \sigma\ A$; $F_s = f_s(\alpha,\beta,\mu)\ \sigma\ A$

Where α = side rake angle; β = back rake angle; μ = cutter-rock friction angle; σ = rock strength; and A = engagement area

Engagement shape tested in previous publications.

In summary:
- Cutter force is proportional to cutter engagement area.
- Almost the same engagement shape is used in all single-cutter tests.

Area-Based Model Does Not Consider Bit Global Design Variables

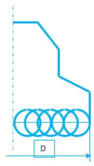
If the cutter penetration force is proportional to the cutting area, namely,

$$F_p^i = k_p^i\ \sigma\ A_i$$

then the following is obtained:

$$WOB = \sum F_p = \sum \left(k_p^i\ \sigma\ A_i\right) = k_p\ \sigma \sum A_i$$

$$= k_p * \sigma\ \frac{D}{2}\ \frac{ROP}{5 * RPM}$$

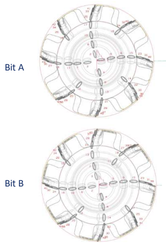


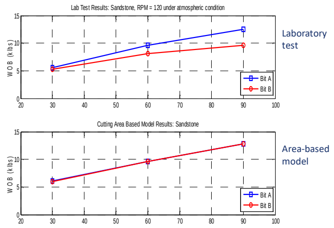
Bit with flat profile

The following is noted:
- Weight on bit (WOB) depends only on cutter rake angles (k_p), rock strength (σ), rev/min, ROP, and bit diameter (D).
- WOB is not dependent on bit global design variables, such as the number of cutters, number of blades, and cutter distributions.

An area-based model cannot be used in PDC bit design optimization.

Example

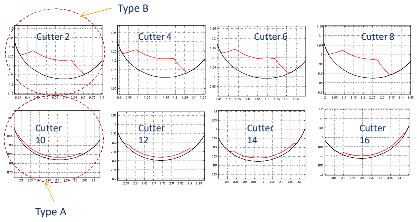




Observation: area-based model cannot differentiate between WOB

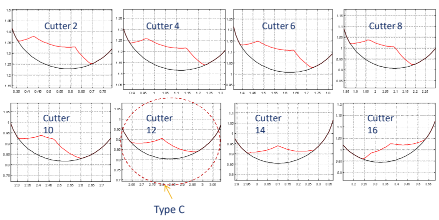
Shapes of Cutter Engagement Area

Cutter engagement area shapes for even cutters on Blade 1, rev/min = 120; ROP = 60 ft/hr
(bit with track-set design)

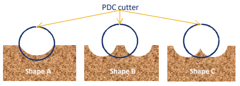


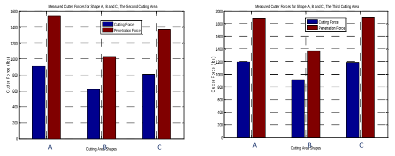
Shapes of Cutter Engagement Area

Cutter engagement area shapes for even cutters on Blade 1, rev/min = 120; ROP = 60 ft/hr
(All cutters are single set)



Three Basic Shapes of Cutter Engagement





Area = 0.021 in.[2]   Area = 0.03 in.[2]

Observation: for the same cutting area, significant differences exist on cutter forces

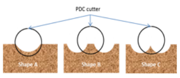
New Cutter Force Model Development: A Common Model

Cutting force

$F_c = k\mu\xi\sigma S^{\alpha} H^{\gamma}$

Where:

- F_c = cutting force
- k = calibration coefficient
- μ = back rake coefficient
- ξ = side rake coefficient
- σ = compressive rock strength
- S = arc length
- H = equivalent cutting height
- α = coefficient from test data
- γ = coefficient from test data

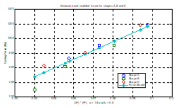


Penetrating force

$F_p = \upsilon F_c \tan(\beta + \varphi)$

Where:

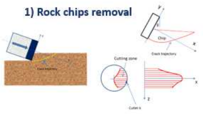
- F_p = penetrating force
- υ = constant coefficient
- F_c = cutting force
- β = back rake angle
- φ = cutter/rock friction angle



Measured and modeled cutting force for Shapes A, B, and C.

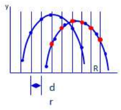
New Bit-Rock Interaction Model Development

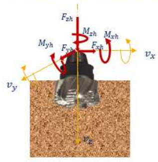
1) Rock chips removal



Two-dimensional (2D) chip created by a cutter (Yan 1997) and expanding 2D chip to three-dimensional (3D) chip

2) Dynamic mesh





3) General bit-rock interaction model

For any given steady-state motion

$d = \{ v_x\ v_y\ v_z\ \varphi_x\ \varphi_y \}$,

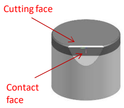
the new bit-rock interaction model outputs

$F = \{F_x\ F_y\ F_z\ M_x\ M_y\ M_z \}$

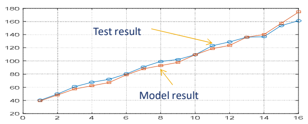
Cutter Wear Considerations

Once the cutter begins to wear, an additional contact area occurs. As a result, additional contact and drag forces are generated.

Laboratory tests were performed for various levels of wear depth and DOC level. The tested rock was sandstone with a rock strength of approximately 4,851 psi.



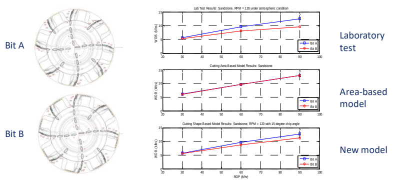
Worn cutter



Drag force: model and test results

New Bit-Rock Interaction Model Development: Model Verification

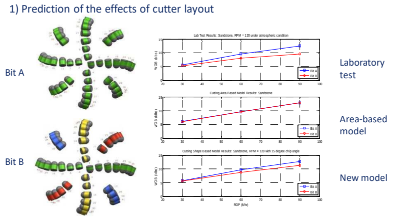
1) Prediction of the effects of cutter layout



Observations:
- Area-based model cannot identify the WOB difference.
- New model successfully predicts the WOB difference.

New Bit-Rock Interaction Model Development: Model Verification

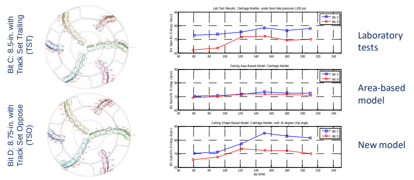
1) Prediction of the effects of cutter layout



Observations:
- Area-based model cannot identify the WOB difference.
- New model successfully predicts the WOB difference.

New Bit-Rock Interaction Model Development: Model Verification

2) Prediction of the effects of track-set



Observations:

- Area-based model cannot identify the difference in drilling efficiency (specific energy).
- New model successfully predicts the difference in drilling efficiency (specific energy).

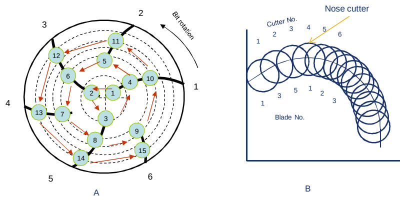
Summary of Part 1

- The area-based bit-rock interaction model, which has been used in the industry for longer than 30 years, fails to predict the effects of bit global design variables on bit performance.
- The shape-based model is able to predict bit drilling efficiency (how fast), bit life (how long), and bit steerability by considering the effects of bit local and global variables.
- The shape-based model is widely verified by laboratory tests and field applications.
- The shape-based model is the basis of bit optimization.

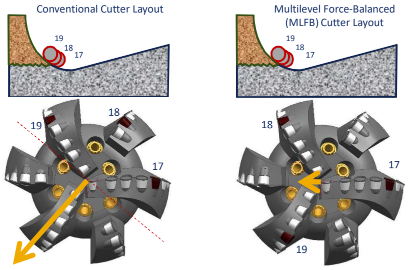
Part 2: New Layout Method for Primary Cutters to Improve Drilling Efficiency

- FB Cutter Groups
- Design Examples
- Laboratory and Field Validation

Conventional Cutter Layout and Its Issues



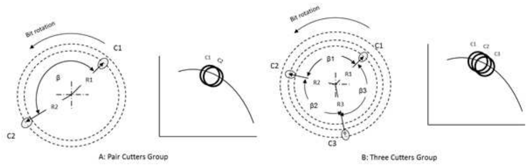
Conventional Cutter Layout and Its Issues



Cutters (17,18,19) are on one side of the bit and can create a significant imbalance force.

Imbalance force created by Cutters (17,18,19) can be self-balanced or minimized.

New Concept: FB Cutter Groups



Pair Cutter Group:
On the profile, they are neighbors; there is no other cutter between them.

They are angularly apart from each other by an angle β > 150° (ideal is 180°).

The imbalance force is minimized.

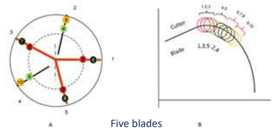
Three-Cutter Group:
On the profile, they are neighbors; there is no other cutter between them.

They are angularly apart from each other by an angle β > 100° (ideal is 120°).

The imbalance force is minimized.

Layout Cutters in FB Groups: Examples

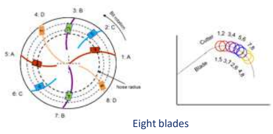
Any **three consecutive cutters**, (1,2,3), (2,3,4), (3,4,5), …, on this five-bladed bit form a **force-balanced group**.



Five blades

Each pair of cutters, (1,2), (3,4), (5,6), (7,8), forms a **force-balanced group**.

Four consecutive cutters, (1,2,3,4), (2,3,4,5), (3,4,5,6), (5,6,7,8), form a **force-balanced group**.

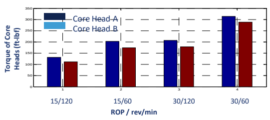


Eight blades

Layout Cutters in FB Groups: Concept Verification By Core Bits Laboratory Tests

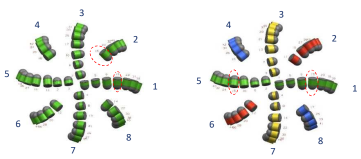
A. Cutters (1,2,3) on one side and (4,5,6) on another side.

B. Six cutters are in two groups: (1,2,3) and (4,5,6).



Drilling efficiency of Core Head B increased **12.75%**

Layout Cutters in FB Groups: Concept Verification by Full Bits

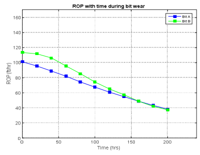


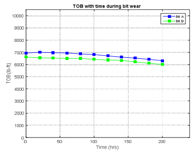
A: Conventional method

B: New method

- Bit A is designed using the conventional cutter layout method. For example, Cutters (15,16) are located on Blades 1 and 2, respectively.
- Bit B is redesigned based on Bit A by relocating some cutters' angular locations so that cutter pair groups are formed (without changing cutter radial locations). For example, Cutters (15,16) are located on Blades 1 and 5, respectively.
- Bit A and Bit B have the same profile, the same number of blades, the same number of cutters, and the same cutter rake angles.

Layout Cutters in FB Groups: Numerical Simulation Results



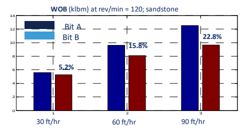


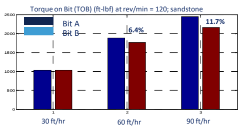
Simulated drilling conditions: rev/min = 120; WOB = 15,000 lbm; rock = 18,000 psi

It is noted that

- Bit B drills faster than Bit A, up to 15% faster
- Bit B has less torque than Bit A, approximately 6.3% less

Layout Cutters in FB Groups: Concept Verification by Full Bit Laboratory Tests





Laboratory tests show

- Bit B drills faster than Bit A—up to 22.8% faster
- Bit B has less torque than Bit A—up to 11.7% less

Laboratory tests results are consistent with the current numerical model results

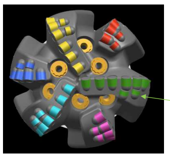
Summary of Part 2

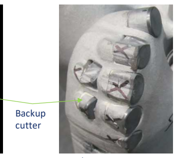
- The numerical model, laboratory tests, and field tests show that the MLFB cutter layout can significantly increase drilling efficiency (without increasing costs).
- The larger the bit, the better the bit performance, according to field application results.
- The MLFB cutter layout has been used since 2012, with thousands of highly successful runs performed globally, particularly in China and the Middle East.

Part 3: New Layout Method for Backup Cutters to Extend Bit Life Without Affecting ROP

- Depth of cut at bit level and at cutter level
- Critical Depth of Cut
- Active and Passive Backup Cutters
- Design Examples and Field Applications

Possible Negative Effects of Backup Cutters


Conventional backup cutter layout

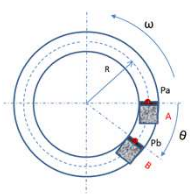


Backup cutters were not properly placed

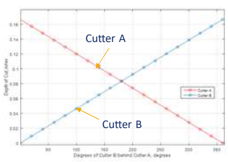
Traditionally, the backup cutter is located rotationally behind its primary cutter, being underexposed. A backup cutter can negatively affect bit life:

- Passively grind rock
- Generate additional heat around cutters
- Negatively affect bit clearing
- Reduce bit ROP
- Increase bit cost without increasing bit life

Concept 1: Depth of Cut (DOC, in/rev)



A & B are 100% track-set



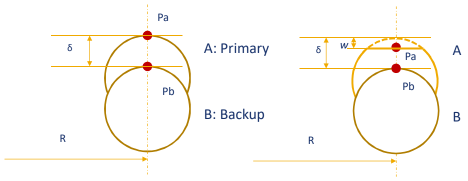
Depth of Cut of A and B as a function of θ

Bit DOC:	$DOC = ROP / (5*RPM)$	in./rev
Cutter B DOC:	$DOC_b = DOC * \theta / 360$	in./rev
Cutter A DOC:	$DOC_a = DOC - DOC_b$	in./rev

- If θ < 180 degrees, cutter A cut deeper than cutter B;
- If θ > 180 degrees, cutter B cut deeper than cutter A;
- If θ = 180 degrees, cutter A and cutter B share equally the depth of cut;

Bit DOC depends only on RPM & ROP, but cutter DOC depends on relative location, θ

Concept 2: Critical Depth of Cut (CDOC, in/rev)

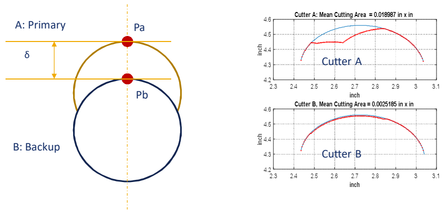


The **critical depth of cut (CDOC) of Cutter B** can be calculated as

$$\Delta c = (\delta - w) * 360 / \theta \quad \text{in./rev}$$

The CDOC is dependent on the underexposure δ, the cutter wear and the angle θ, CDOC can be designed.

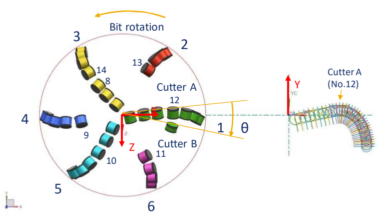
Concept 3: Active & Passive Cutters



Backup cutter B is underexposed relative to primary cutter A.

- Cutter B is a passive cutter due to its very low DOC;
- Cutter A is an active cutter;

Example 1: No cutter wear and no underexposure



An example bit with only one backup cutter (Cutter B) with angular location (angle θ)

- Cutter A and Cutter B are track-set cutters;
- No underexposure for cutter B;
- Cutter A is on blade 1, cutter B may be on any blade from 1 ~ 6.

Example 1: No cutter wear and no underexposure

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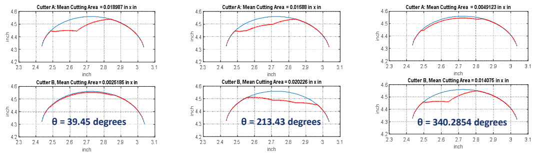

Case 1: θ = 39.45°.

Cutter B is a passive cutter, and Cutter A is an active cutter.

Cutter B may have low drilling efficiency.

Case 2: θ = 213.43°.

Cutters A and B are both active cutters.

Both Cutters A and B have high drilling efficiency.

Case 3: θ = 340.28°.

Cutter B becomes an active cutter, and Cutter A becomes a passive cutter.

Cutter A may have low drilling efficiency.

For Cutter B to effectively cut, its angle θ needs to be greater than 180°

Example 2: Cutter wears and underexposure

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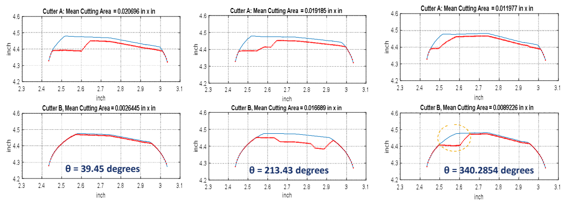

Case 1: θ = 39.45°.

Backup cutter B is a passive cutter.

Cutter B may have low drilling efficiency.

Case 2: θ = 213.43°.

Backup cutters B is an active cutter.

Both Cutters A and B have high drilling efficiency.

Case 3: θ = 340.28°.

Backup cutter B partially an active cutter

Cutter B may have high drilling efficiency.

For Backup cutter B to an active cutter, its angle θ needs to be greater than 180°

Basic Requirements on Backup Cutters

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The location of a backup cutter should meet the following conditions:

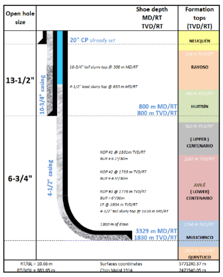
- Track-set with its primary cutter (with potential to become a backup cutter).
- Angular location relative to its primary cutter, θ >= 180.0 (to act as a primary cutter when needed).
- Δc >= Δc0, the expected DOC when its primary cutter experiences no wear (to ensure backup cutter does not engage when DOC < Δc).
- Underexposed, δ >= wc, the expected wear depth of its primary cutter (to begin to fully engage when its primary cutter experiences wear of wc).

Case Study: Field Applications in Argentina

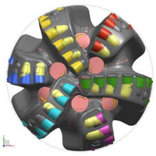
Background

- 6 3/4-in. Lateral section with a tight and abrasive sandstone known as Mulichinco.
- Heavy wear sustained by the nose cutters and shoulder cutters, which caused a rapid decrease in ROP.
- Several PDC bits (at least 3) were necessary to drill through this 1100-m section.

Directional Program



Case Study: Field Applications in Argentina



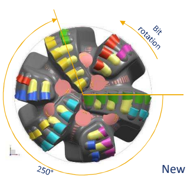
Standard (conventional) design

Heavy cutter wear

Measured depth (MD) in (m)	2538
MD out (m)	2919
Length drilled (m)	381
ROP (m/h)	6.71

Heavy cutter wear was observed on conventional bits.

New Bit Design with Optimal Backup Cutters



MD in (m)	1786
MD out (m)	2538
Length drilled (m)	752
ROP (m/h)	6.32

New design

The new bit doubled the drilling distance with almost the same level of ROP.

Dull Conditions

Much better dull conditions are observed for the new bit.

Summary of Part 3

- A backup cutter and its primary cutter should be "track-set."
- A backup cutter should be located rotationally behind its primary cutter at an angle of greater than approximately 180°.
- The underexposure of a backup cutter should be carefully selected.
- Field applications of the new bits designed using this method show significantly extended bit life without detrimentally affecting ROP.

References

This presentation is based on the following references:

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- Chen, S., Khlefat, Y., Cleboski, C. et al. 2017. A New Method of Layout Back-up Cutters to Extend Bit Life Without Sacrificing Rate of Penetration. Presented at the SPE Kuwait Oil & Gas Show and Conference, Kuwait City, Kuwait, 15–18 October. SPE-187644-MS.
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