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Modelling the 3D Bit-Rock Interaction Helps Designing Better PDC Bits

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Abstract

The bit-rock interaction has long been studied to assess PDC drill bit performance, which is driven both by cutting and non-cutting parts of the drill bit. While the cutter-rock interaction has been studied by many authors in the literature, only a few studies have focused on the interaction between the rock and non-cutting parts of the drill bit.

In this paper, we introduce a new method designed to model the interaction between the whole drill bit and the rock formation within a full three-dimensional framework. This approach is based on a generic computational geometry algorithm which simulates the drilling process considering both the drill bit and the hole being drilled as a set of 3D meshed surfaces. The volume of rock removed by the PDC cutters as well as the area and the volume of contact between the rock and the non-cutting parts of the drill bit can be computed with a high accuracy based on the 3D CAD model of the drill bit.

The in-house drill bit simulator implementing this algorithm primarily allows the engineer to estimate how bit-rock interactions distribute between cutting and non-cutting parts of the drill bit and to balance the bit design in the 3D space accordingly over a given range of drilling parameters. This approach has been brought to the field in order to address cutter breakage based on rubbing contacts optimization. Field results associated to some case studies in US shale plays and Canada are described and clearly show that contact points predictions closely match field observations. Moreover, design modifications applied following this process have led to an overall increase in bit performance and bit durability while preventing core-out issues.

The bit design methodology presented in this paper is dedicated to design drill bits whose interaction with the rock formation is predicted with a higher accuracy by accounting for the exact 3D shape of the drill bit.

Introduction

Background

Drillbit simulators have been used in the oil and gas drilling industry for many decades to allow bit manufacturers to estimate the drill bit mechanical response of Roller Cone bits (RC) and Polycrystalline Diamond Compact bits (PDC). The use of a simulator for pre-run or post-run analysis supports the bit engineer in his daily task to identify an optimized design for a given drilling application. The bit engineer can either focus on the estimation of the drill bit performance (Dupriest and Koederitz, 2005), the balancing of the bit design using some force, global or energy balancing techniques (Clayton et al., 2005), its dynamic stability (Oueslati et al., 2014), its directional performance including gage design (Menand et al., 2004; Mensa-Wilmot et al., 2006) and tool face control (Chen et al., 2007; Barton et al., 2009) or a combination of all the above (Spencer et al., 2013).

Principle of a bit simulator

A bit simulator basically aims at establishing the relationship between bit kinematic quantities (e.g. ROP, RPM, bit tilt) and bit mechanical quantities (e.g. WOB, TOB or side force). It can be used in a standalone mode (kinematic approach): the bit motion is prescribed, and the resulting interaction forces are computed (Sellami and Cordelier, 1991; Behr et al., 1993; Gerbaud et al., 2006; Chen et al., 2007). It can also be coupled to a drill string simulator (static or dynamic approach): the bit motion and the interaction forces are both computed through an iterative process based on the drill string movement equations (Langeveld 1992; Hanson and Hansen, 1995; Dykstra et al., 2001; Spencer et al., 2013). When the drill bit is suspected to play a major role in the drill string mechanical response, an advanced bit simulator able to describe the bit design in detail should be preferred (Chen et al., 2007; Spencer et al., 2013). Otherwise, a more simplified drill bit model may be sufficient (Yigit and Christoforou, 2006; Richard et al., 2007).

Existing 3D bit simulators

Bit simulators can be split into 2D and 3D rock modellers, the drill bit being always modelled in 3D. 2D bit simulators (rock modellers) are based on the assumption that the cutting section of each cutter is constant over a full revolution of the drill bit which makes it possible to compute the hole geometry by projecting each cutter shape in a vertical plane crossing the main axis of the drill bit (Warren and Sinor, 1986; Glowka, 1987; Sellami and Cordelier, 1991; Clayton et al., 2005; Cuillier et al., 2017; Curry et al., 2017). Such simulators accurately predict PDC cutting sections provided that the drill bit movement respect this assumption (constant ROP and constant RPM). However, they do not apply to RC bits and to PDC bits subjected to complex movements, like directional trajectories with a tilted bit, motor rotating movements or lateral vibrations. For this purpose, 3D bit simulators are needed.

As early as in 1985, Baird et al. develop a 3D drill string simulator which includes a 3D drill bit simulator interacting with a 3D hole geometry. One of the purposes of this pioneering work is to understand the influence of the design of PDC bits on BHA dynamics. Although the bit/rock cutting and contact interactions are modelled in a full 3D framework giving an insight into advanced bit design considerations, rock removal at the formation/bit interace is not accounted for. Langeveld (1992) develops an alternative approach which includes the rock removal process and focuses on PDC bit dynamics. The description of the drill string is reduced to 4 degrees of freedom (DOF) while the hole is modelled as a set of radially meshed 3D contours (2D grid), updated at each cutter pass. However, gage pads are considered as perfect cylinders (1D description) which hinders advanced gage design optimization. Behr et al. (1993) improve the 2D bit simulator presented in Warren and Sinor (1986) to account for the 3D description of the hole geometry, defined as a series of regularly spaced and radially meshed radial planes (2D grid). This 3D bit simulator allows the authors to analyze how PDC cutter loads evolve when drilling heterogeneous rock formations as well as the impact of the cutting structure imbalance on the occurrence of bit whirl. In this model, the bit movement is prescribed rather than calculated within a drill string simulator, and bit/hole contacts are not considered.

Hanson and Hansen (1995) implement a 3D drill string simulator which is similar to the one from Behr et al. (1993) in terms of hole description, except that radial planes are also meshed vertically (3D grid). It becomes possible to simulate a greater variety of drilling scenarios like high penetration rates and extreme lateral vibrations. In terms of drill string description (5 DOF) and bit/hole contacts modelling, the authors follows a similar approach to the one from Langeveld (1992), except that the contact algorithm is improved to account for energy loss and better numerical performance. Dykstra et al. (2001) presents a first major evolution of the model of Hanson and Hansen (1995) which can now simulate RC bits, and which can be coupled either to the same few DOF drill string simulator or to a Finite Element Model of the whole BHA. The authors demonstrate how such advanced dynamic models can improve the whole drilling system design and operation.

To our knowledge, Chen et al. (2007) are the first to develop a 3D bit simulator which focuses on the modelling of the bit contact parts. Just like cutters, these parts are modelled as "cutlets" which interfere with the rock and allow to compute both the bottomhole pattern and the rock removed by each cutlet. Separate physical models are defined to account for the interaction of cutters, active gages and passive gages with the rock. Based on prescribed directional trajectories and bit movement, the authors simulate several directional drilling scenarios to show the influence of the bit design (gages in particular), on the bit steerability and walk.

Endres (2007) presents a novel kind of 3D bit simulator for both PDC and RC drill bits to overcome the lack of resolution of all the above models in the outer part of the hole, which comes from the way the hole is meshed based on radially oriented contours or planes. The drill bit and the hole geometries are both modelled as 3D triangulated surfaces and the rock removal process is achieved by updating the position of each vertex of the rock surface model each time a cutting element interfere with it. Although the updating process depends on the bit geometry, the overall numerical process ensures a good quality of the resulting meshes both in terms of resolution and size. Bit/hole contacts are not considered, but the author demonstrates how this model can simulate complex PDC and RC bit movements.

Spencer et al. (2013) presents a second major evolution of the model of Hanson and Hansen (1995) with the introduction of distributed contact modelling. This new approach allows to define the bit design with a higher accuracy, the gage pads and blade tops being modelled as 3D objects delimited by 2D polygons. Based on the same drill string simulator as in Hansen and Hansen (1995), the authors show the close link between the dynamic stability of a drill bit and tool face control.

Alhtough Oueslati et al. (2014) do not focus on 3D bit simulations, they illustrate the impact of depth of cut variations undergone during stick-slip cycles on the development of rubbing grooves on the blade tops of PDC cutter substrates and ultimately on PDC bit damage. The corresponding model is not described in detail. However, it illustrates well the interest of modelling distributed contacts on PDC bits.

In this paper, we introduce a new method designed to model the interaction between any given PDC drill bit geometry and the rock formation within a full 3D framework. In the straight line of the simulators presented above, both the cutting parts and the non-cutting parts of the drill bit are modelled. The novelty of the presented work is double: first, the rock removal process is achieved based on a new approach which ensures a high accuracy of the resulting geometric models; second, the distributed contacts over the drill bit are modelled based on the exact CAD representation of the gages, the blades or the cutters and not on some geometric approximation of it. The goal of this approach is to provide the application engineer the most accurate tool to optimize the bit design.

Decoupling bit kinematics and mechanics

No matter whether the drill bit simulator is coupled to a drill string simulator or not, it is generally assumed that the computation of the interaction forces is decoupled from the computation of the interaction geometry. In the case of RC bits, tooth/rock interaction models aim, first, at estimating the dimension of the crater of rock removed, which is much larger than the exact volume occupied by the tooth itself due to the fragile nature of the indentation process; second, at estimating the interaction forces which result from this geometry of interaction based on analytical expressions that can be conveniently used in bit simulators (Ma et al., 1995). In the case of PDC bits, cutters mainly destroy the rock following an elasto-plastic process. Thus, the cutter groove geometry can be well approximated by the exact volume swept by the cutter along its trajectory. Hence, PDC cutter/rock interaction models only aim at estimating the interaction forces which result from this somehow simpler interaction geometry. These models too are generally based on analytical expressions for the same reasons. The work presented here is made under this decoupling assumption, just like other existing bit simulators presented in the previous section.

Note that modelling the rock as a deformable solid with a given rheology would make the estimation of the interaction forces more accurate. However, it would require running a numerical model for all cutters of a given drillbit which would drastically increase the complexity of the whole process both in terms of algorithm convergence and computation time. This would also require the user to know the rheology of the rock being drilled, which is generally not the case in daily drilling operations. In practice this approach is not developed in the field of Oil and Gas drill bit mechanics, rather in the field of metal machining (Cohen-Assouline, 2005; Marty, 2003) where the access to this knowledge is more straight-forward.

Geometric modelling

PDC cutter movements and shapes

The results presented in this paper have been obtained using the 3D bit simulator in a standalone mode. As explained above, in this case the drill bit movement along a given well trajectory must be prescribed. Well trajectories modelled in the bit simulator address most common drilling applications (Chen et al., 2007): vertical/tangent sections (Fig. 1a); build-up/drop sections (Fig. 1b); kick-off sections (Fig. 1c). In order to drill the curve, the drill bit must be tilted thanks to the directional system. The relationship between the applied bit tilt and the resulting build rate can be well approximated using the classic 3-point geometry formula or some refined version of it (Marchand and Kalantari, 2013).

The movement of a tilted drill bit subjected to a rotation around its own axis (single-axis rotation) significantly departs (Fig. 1b, **c**) from a simple helix (Fig. 1a). When a mud motor is used in the rotating mode, an additional rotation is applied around the motor's stator (double-axis rotation), which results in an eccentric bit movement and an irregular bottomhole pattern (Fig. 1d). This movement presents some similarities with the bit whirl movement (Brett et al., 1989) including that some inner cutters may drill the rock with the side of the diamond table or even may rotate backwards. Eventually, this can lead to cutter breakage and core-out issues putting a stop to drilling operations.

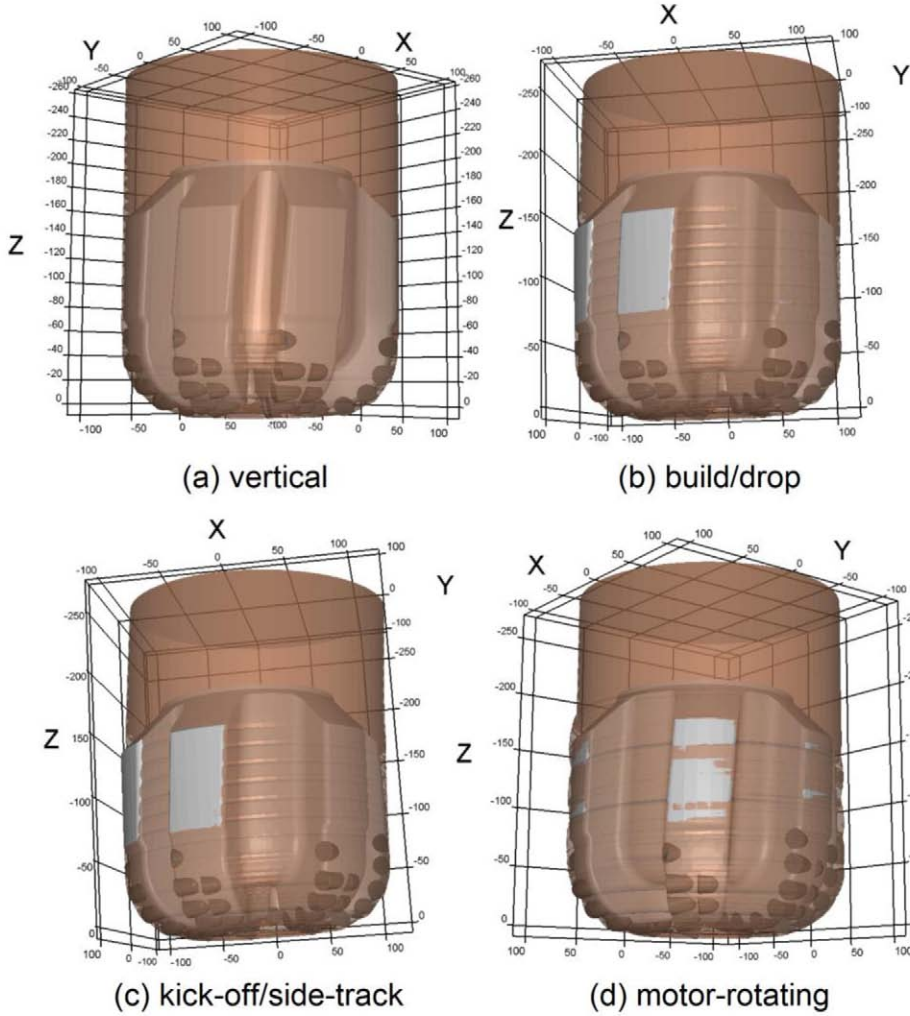

Figure 1—examples of simulated bit trajectories and movements

The rock removal algorithm also needs to take into account the variety of cutter shapes that are currently disrupting the PDC bit market (Endress, 2017). To be able to adapt this algorithm to a constantly evolving set of cutter shapes and movements, a generic approach has been developed which makes minimal assumptions on the cutting geometry and kinematics.

Bit-rock interactions based on boolean operations

All geometric interactions between the drill bit and the rock are computed based on boolean operations between 3D models. It applies to both the process of rock removal by bit cutting parts and the estimation of the geometry of contact between the rock and bit contact parts. There are two main approaches to handle such operations: the discrete approach consists in discretizing the interacting 3D models either as 2D grids (Langeveld, 1992; Lee and Ko, 2002; Cohen-Assouline, 2005) or as 3D grids (Hanson and Hansen, 1995; Lee and Nestler, 2012; Landier, 2017) and perform boolean operations based on these finite objects with regular intervals (Kaneko and Horio, 2013); the second approach consists in representing the interacting 3D models using their Boundary Representation (BREP) either as parametric surfaces (Barki et al., 2015) or as 3D triangulated surface meshes (Schifko et al., 2010; Caron, 2013; Landier, 2017).

The latter approach has been preferred because it is not constrained by an a priori isotropic accuracy like the discrete approach. Thus, it allows to detect and estimate the tiniest geometric interactions between the rock formation and the drill bit, like thin contacts on gage pads, on blade tops or on the back of the cutters, which was one of our primary goals.

Rock removal and sweeping algorithm

To compute the volume of rock removed by any cutter geometry based on the sole knowledge of its triangulation and movement requires to implement a so-called swept volume algorithm. This is a classic problem in computational geometry with numerous applications in the field of geometric modelling, collision detection, robot workspace analysis, motion planning and Numerically Controlled machining (Kaneko and Horio, 2013; Kim et al., 2004). First, the process consists in computing the active surface of a given cutter animated by a given movement. The active surface of a triangulated object being defined as the set of "visible" facets of this object in movement. In other words, a facet is "visible" if the angle between the normal to this facet and its local movement vector is less than 90°. Based on this computation, active surfaces are generated incrementally (Fig. 2, left). Then, they are connected to form the swept volume which is positioned in the hole to achieve the rock removal process (Fig. 2, right).

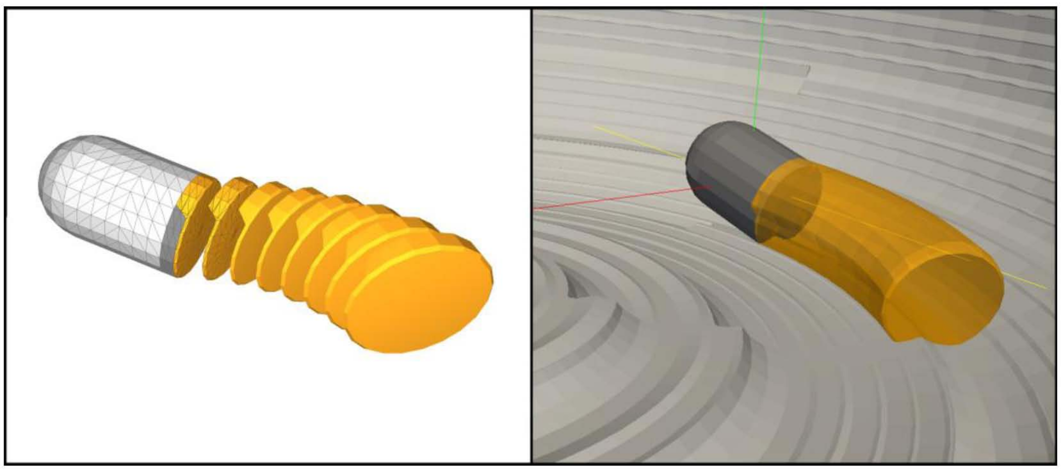

Figure 2—left, a series of active surfaces (orange) associated to the diamond table (heavy grey) of a cutter (light grey); right, the resulting swept volume (orange) before rock removal.

Then, from a given initial hole geometry (Fig. 3, left), the bottomhole pattern is updated incrementally by computing the boolean difference between the hole geometry at the previous step and all cutters swept volumes. This is illustrated in Fig. 3 (center and right) where the drill bit has been rotated and translated twice to generate two consecutive bottomhole patterns.

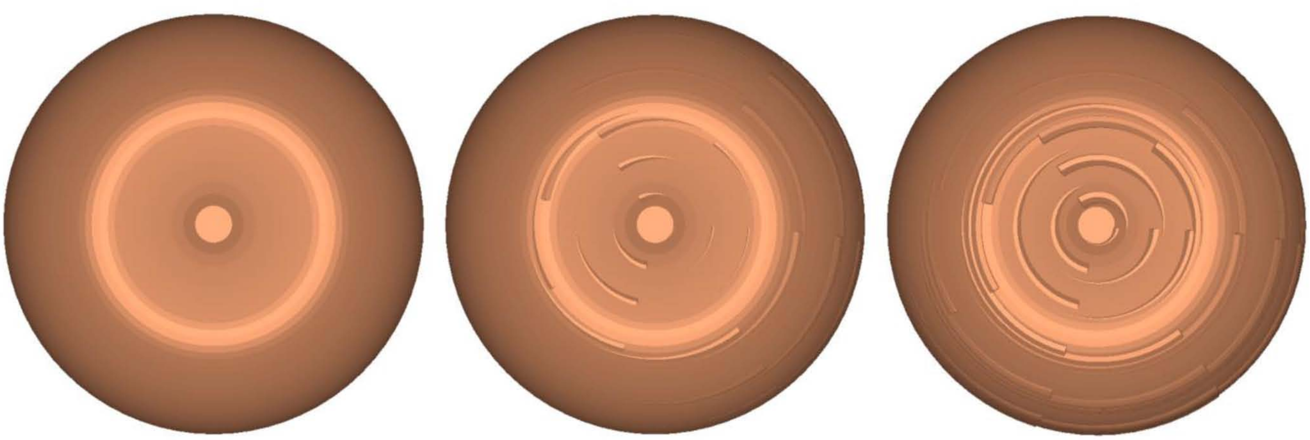

Figure 3—from an initial 3D model (left), the bottomhole pattern is computed by moving the bit incrementally along its trajectory (center, right); note that hole geometries shown represent the negative view of the real hole geometry

As illustrated in Fig. 4 (left and center), the swept volume is also used to compute the volume of rock removed by each cutter. Fig. 4 (right) also shows that the contribution of each cutter parts to the rock removal process can be identified and estimated independently.

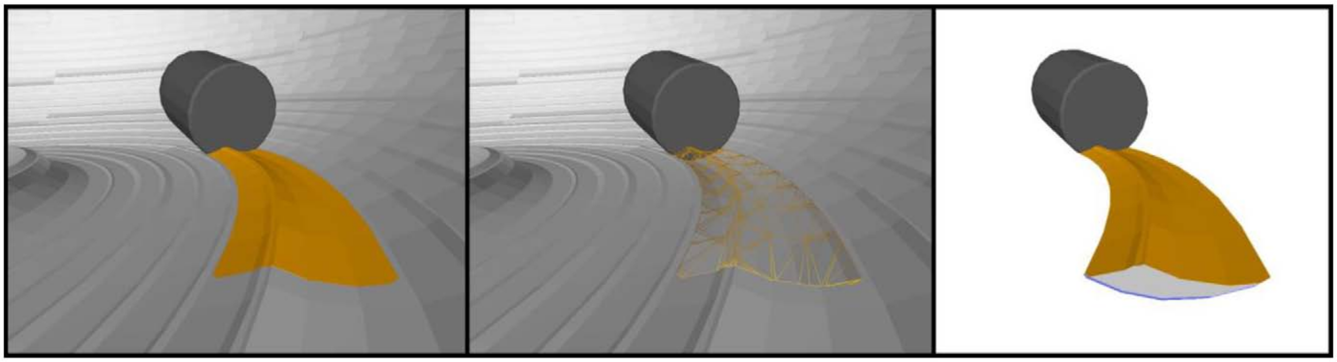

Figure 4—left, a view of the volume of the rock removed (orange); center, the same in wireframe mode; right, the same where the contribution of each cutter parts has been identified (blue=chamfer section, light grey=cutting section, orange=free surface)

The swept volume algorithm being generic, it applies to any shaped cutter geometry as shown in Fig. 5.

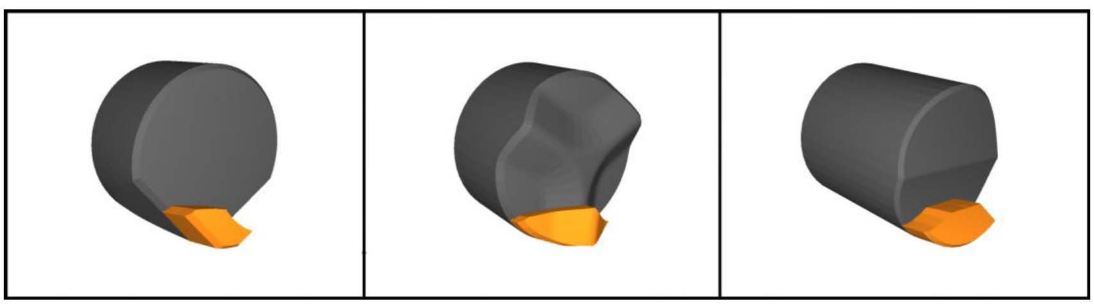

Figure 5—the generic swept volume algorithm can simulate any existing 3D shaped cutters

Numerical aspects

The development of such a 3D geometric model raises numerical issues in terms of robustness, accuracy and performance. Some authors in the field of metal machining have long identified these limits when using boolean operations on polyhedron, considered then as a relatively slow numerical process with a lack of robustness (Lee and Ko, 2002; Marty, 2003; Cohen-Assouline, 2005). To overcome these issues, the core algorithms of the simulator are based on the open source CGAL library, which was created in 1995 and has become a major reference in the field of computational geometry (Campen and Kobbelt, 2010; Schifko et al., 2010; Barki et al., 2015; Landier, 2017). It has benefited the latest research advances on geometry kernels with exact/inexact predicates/constructions (Pion and Fabri, 2011), on the numerical representation of polyhedra (Botsch et al., 2018) or on the definition of structures for the detection of intersections (Alliez et al., 2017).

Computing the bit/rock interaction with a robust and accurate geometric model is time and memory consuming. In terms of data volumetry, the bottomhole pattern drilled by a bit over its own height typically contains 100-500k vertices which represents roughly 10-50Mb depending on the geometric file format. As explained above, a simulation can contain tens of those to be able to describe with accuracy the dynamic response of a drillbit in complex drilling scenarios. The simulation time to perform these calculations is typically in the range of 1-10min depending on the bit geometry and movement. However, depending on the drilling scenario and the operational objective of the analysis there are several options to accelerate computations, like 3D model simplification or algorithm parallelization.

Physical modelling

Based on the computation of these geometric interactions, the associated cutting and contact forces are computed as has been done in many drill bit simulators in the past (Chen et al., 2007; Spencer et al., 2013). This computation is based on existing physical models which relate fundamental geometric quantities to rock mechanics quantities through analytical expressions. Such formula-based models can be theoretical in which case they apply to a variety of rocks but present less flexibility to be adjusted on actual lab or field data (Sellami et al., 1989; Gerbaud, 1999; Detournay and Atkinson, 2000; Amri, 2016). Or they can present some degree of empirism in which case they mainly apply to well instrumented drilling cases (Detournay and Defourny, 1992; Richard et al., 1998; Pelfrene 2010). To account for the variety of drilling contexts and the accessibility of lab/field data, several cutting models have been implemented in our simulator. Basically, they follow the same schematic description of the rock cutting process (Fig. 6).

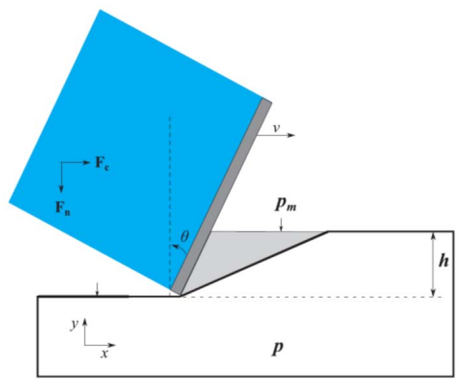

Figure 6—schematic description of a cutting model (Amri et al., 2018)

Where F_n and F_c designate the normal and tangential components of the cutting force; v the cutting speed; h the depth of cut; θ the back-rake angle; p_m and p the mud pressure and the initial pore pressure. Depending on the version in use, the cutting model can also embrace more general 3D shape parameters, hydro-mechanical parameters related to the rock strength and diffusivity or interfacial friction factors. They all follow some analytical expressions of the form:

$$(F_n, F_c) = f\left(G_{cutting}, v_{cutting}, K_{rock}, C_{rock}, D_{rock}, P\right)$$

Where $G_{cutting}$ encompasses the cutting geometry parameters (depth of cut, cutting angles, etc.), $v_{cutting}$ the cutting velocity, K_{rock} the rock strength parameters, C_{rock} the bit/rock and rock/rock frictional parameters, D_{rock} rock/fluid diffusivity parameters and P the mud pressure and the pore pressure. These analytical expressions are used to compute cutting forces (Fig.7).

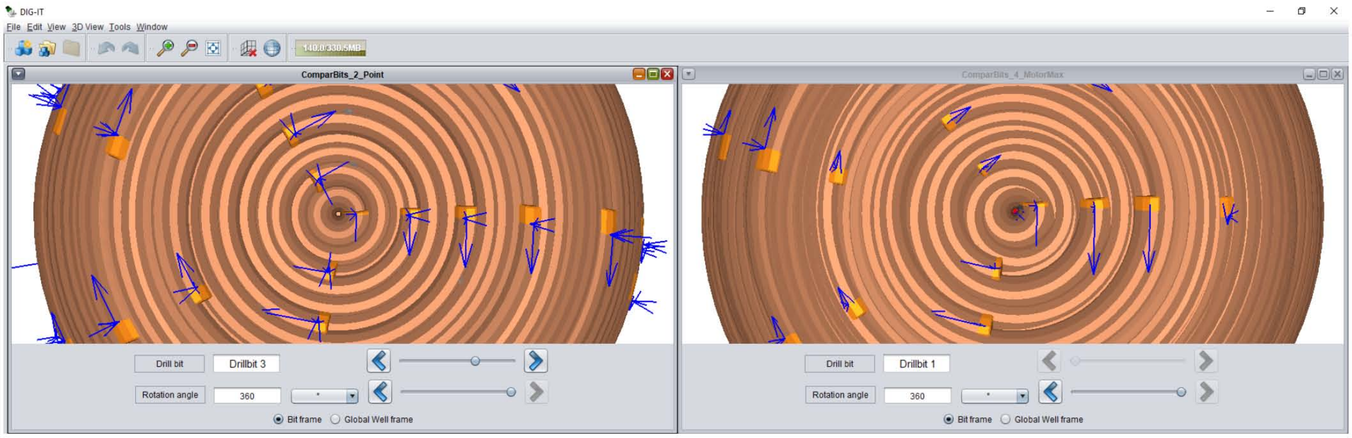

Figure 7—cutting forces (blue) and cutting volumes (orange) for two drilling scenarios (left, point-the-bit; right, motor-rotating)

These models inherit from the research work developed by Sellami et al. (1989), Gerbaud (1999), Menand (2001), Gerbaud et al. (2006), Pelfrene (2010) and Amri (2016). The semi-analytical model (analytical/ numerical) developed by Amri (2016) has the particularity to address the rate-dependence of cutting forces under pressurized conditions. It has been developed to investigate the dynamic confinement phenomenon and bit-related stick-slip issues which have been shown to be linked with the rate-dependence of the cutting model (Pelfrene et al., 2011; Jain et al., 2011). However, as all existing analytical models, it simplifies the physics of the rock cutting process. Hence, a numerical model based on the Finite Element Method has also been developed to reinforce the conclusion that cutting forces explicitly depend on the cutting speed under pressurized conditions (Amri et al., 2018). Lab validation of this promising model has been presented in Amri et al. (2016) and field validation is under development. Note that rate-independent cutting models generally match well field results in usual drilling contexts, provided that they do not involve dynamic confinement or bit-related stick-slip. This is not surprising since most of them are calibrated on extensive experimental single cutter data sets and validated at the drill bit scale (Zijsling, 1987; Glowka, 1989; Richard et al., 1998; Gerbaud et al., 2006; Pelfrene, 2010; Amri et al., 2016).

The contact model implemented is based on the Hertz contact model with the assumption that bit contact parts are infinitely rigid in comparison to the rock. This model follows:

$$F_n = \frac{4}{3} E^* a \delta \quad ; \quad F_c = \mu * F_n$$

Where $E^* = E/(1\text{-}\nu^2)$, E designates the Young's modulus of the rock, ν the Poisson ratio of the rock, a the radius of the contact surface, δ the normal displacement of the interface, and μ the solid friction coefficient between the rock and the bit contact part. In theory, this model only applies to non-adhesive elastic sphere/plane contacts. Bit/hole contact interactions clearly deviate from this simple assumption due to the complexity of both the geometry of contacts (Fig. 8) and the rheology of the physical bodies in interaction. Hence, this model should be considered as a first approximation of contact forces. Some research work is under development to improve it. Note that this uncertainty in the quantitative analysis of contact forces does not prevent the bit engineer from conducting a qualitative analysis of contacts. More specifically, estimating how a bit performs in terms of aggressiveness, balancing, steerability or tool face control in comparison to another one remains a reliable option.

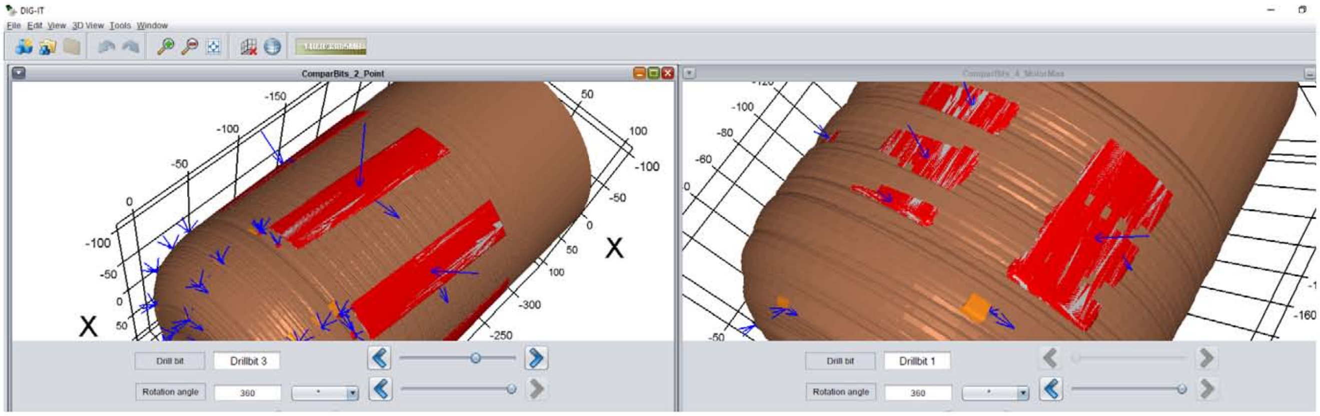

Figure 8—contact forces (blue) and contact volumes (red) for two drilling scenarios (left, point-the-bit; right, motor-rotating)

Since all the physical models implemented in our simulator are based on analytical or semi-analytical expressions, the computation of the interaction forces is almost instantaneous in comparison to the computation of the geometric model and does not add any numerical issue. This approach has the advantage of being sufficiently robust and fast to be deployed and used daily by application engineers for in-depth bit design optimization (Carlos, 2017; Cuillier et al., 2017).

Model applications

3D bit design optimization

The simulator provides a variety of interpretation tools (Fig. 9) which allow the application engineer to conduct a detailed analysis either at the cutter scale, based on local cutting and contact forces, or at the bit scale, after integration of local forces over the drill bit to compute outputs like WOB, TOB, specific energy, side force, walk angle or other bit performance indicators like DRIMP (de Reynal, 2009). At the cutter scale, cutter graphs are used to optimize cutter placement or cutter load distribution. When dealing with complex bit movements, it also allows to detect huge load variations. At the bit scale, spider graphs are used to grade bit designs according to performance criteria like steerability, stability or aggressiveness. Dynamic curves allow to analyze the stability of the drill bit, particularly to ensure that the tool face orientation is stable. Rubbing curves are another example of an interpretation tool which help finding the optimal drilling parameters for a given application.

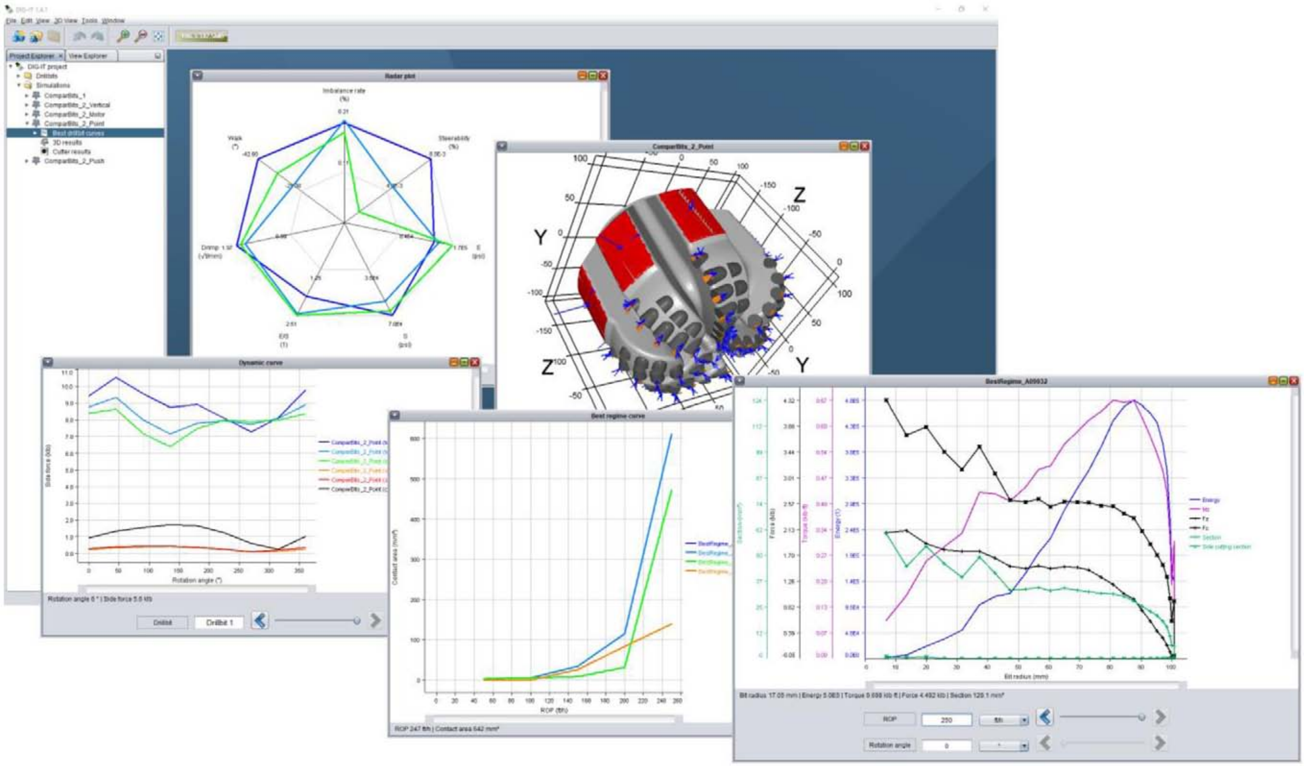

Figure 9—a series of interpretation tools used to optimize bit designs

An often-underestimated use of a bit simulator consists in analyzing the geometry of the bit/rock interaction prior to any force computation. Indeed, this is of great help for the bit designer who can thus check basic but critical design criteria. Fig. 10 shows an example where the bit designer needs to check that the point loads of the secondary row shaped cutters are correctly positioned on the bit body. The simulation reveals that most of them engage the rock, sometimes showing several connected components, while some others do not. Such a simulation provides some clues about bit design weaknesses.

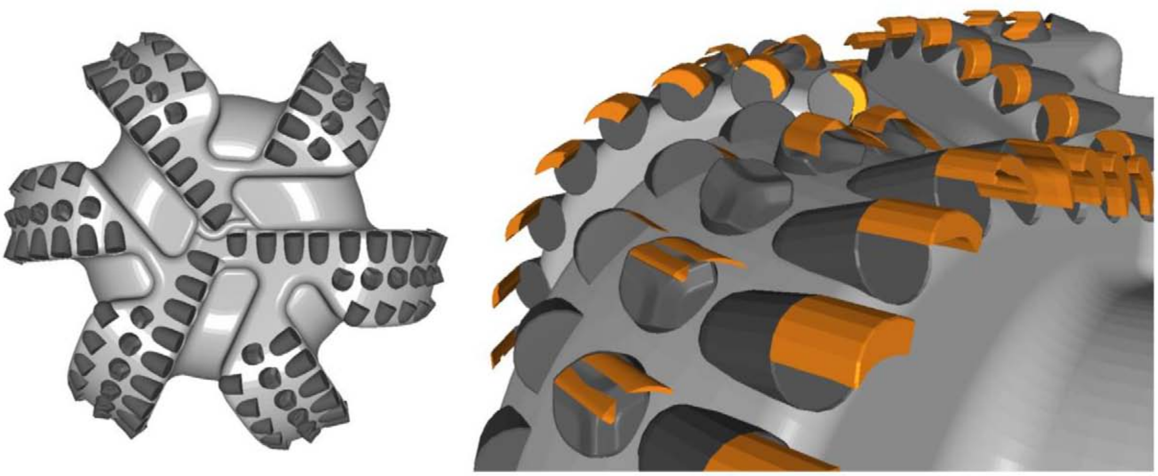

Figure 10—example simulation performed to optimize placement of 3D shaped cutters point loads

This approach has been proven to be reliable in many drilling applications as can be seen in Fig. 11 where the matching between simulated and field rubbing areas is very accurate.

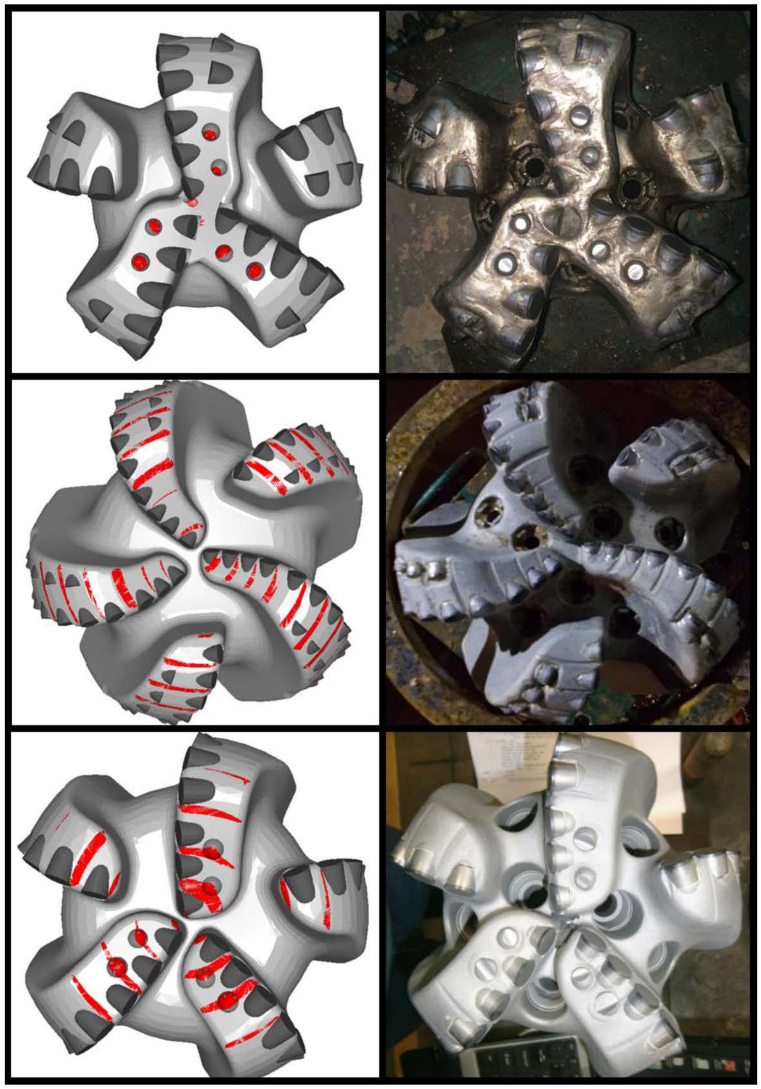

Figure 11—simulations accurately predict field observed rubbing areas; left, 8"1/2 VS516PDGHUX West Texas run; center, 11"5/8 V516PDG1H Russia run; right, 8"1/2 V516DHX South Texas run

Case study #1 – solving core-out issues with a bent motor (Canada)

It is crucial in bit design that the cone cutters are placed to minimize large variances in resultant forces and sections between cutters. This is easy to accomplish with the appropriate concentric rotation bit designer program (2D bit simulator). However, a drill bit rarely drills around its center axis of rotation. Coupled with a bent motor a drill bit will generally rotate eccentrically more than 75% of the time during normal vertical and lateral drilling operations. Such eccentric movements generate large variations in cutter sections and forces which may lead to catastrophic breakage through overloading.

In Canada, an 8.75" with 7 blades and 16mm cutters bit was designed for central Alberta drill out applications where multiple soft to hard formations would be encountered through the interval. In the beginning, drilling performance was exceptional. However, from time to time cutters in the cone were badly delaminated and broken while the nose and shoulder cutters were in good condition. This damage became more consistent as the operator pushed the bits harder. This sparked an initiative to redesign the bit to alleviate cone cutter damage. Two design attempts were made without success (Fig. 12, left, center).

Figure 12—left, center, 2 offset bits showing cone cutter breakage; right, the new bit design pulled out green

The need for a fast but resilient 716 drill bit grew and therefore a cause to why the cone cutters were breaking was needed. All bit designs were run through the bit simulator using a bent housing motor in the rotating mode. Looking at each cone cutter as the bit rotated eccentrically revealed that the cutters were being subjected to large swings in load, section and DOC. It was also found that the bit cone was rather deep (Fig. 13, left). A deep cone will allow for more cutters to be placed in the cone, but it will also create a so-called formation core in the center of the bit as it drills ahead. If the bit is drilling eccentrically the cone cutters will bite into the side of the formation core. As the bit rotates further the cutters will pull away from the core and substantially drop its effective depth of cut and resulting forces. This continuous swing in large depth of cut to little to no depth of cut puts a large strain on the cutters through cyclic loading as can be seen in Fig. 13 (right).

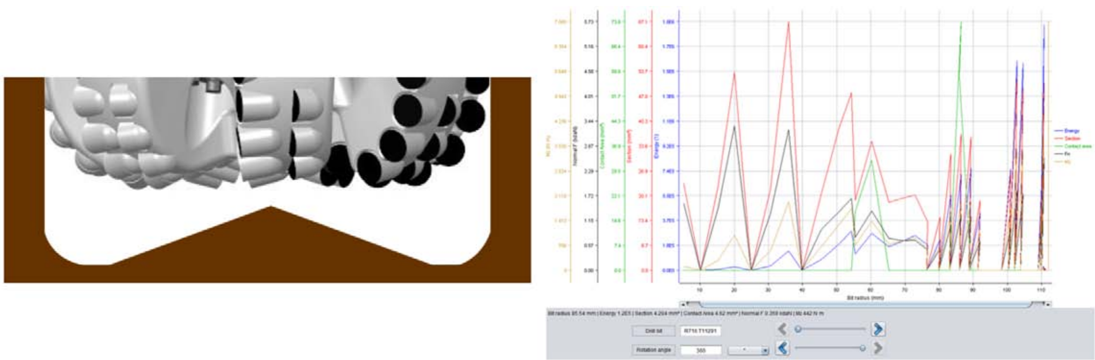

Figure 13—offset bit design with a deep cone (left) showing huge cutter cyclic loading as the bit drills eccentrically (right)

With this new data in hand a new design was created using a much shallower cone – 50% reduction in cone angle (Fig. 14, left). The new design was then run through the bit simulator. A substantial decrease in cyclical loading and resultant forces was observed (Fig. 14, right). As of October 2018, the new bit design has been run 4 times with no occurrences of cone cutter damage (Fig. 12, right).

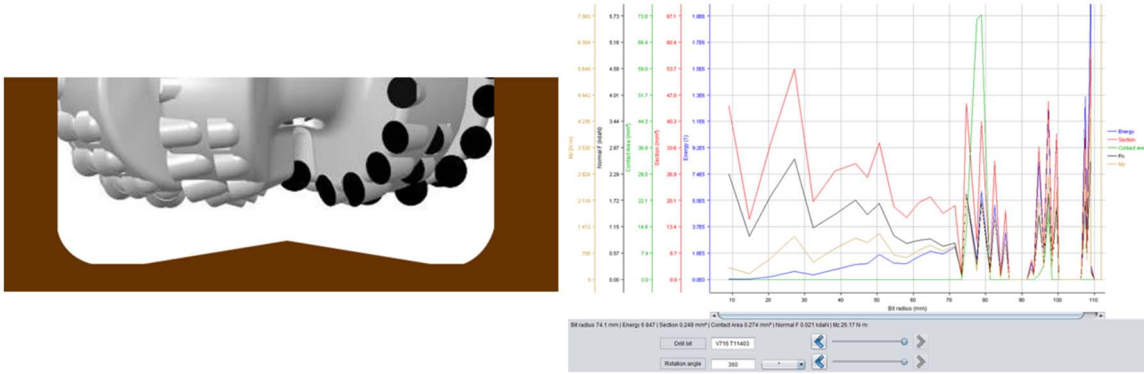

Figure 14—new bit design with a shallow cone (left) showing reduced cutter cyclic loading as the bit drills eccentrically (right)

Case study #2 – preventing cone cutter breakage (South Texas)

For this Eagleford shale application in South Texas, the target was to drill the curve and the lateral sections. In this area, the formations drilled are primarily sand and shale with traces of limestone throughout. Those sections are typically from 10,000 feet to 16,000 feet drilled length, at an average ROP of 120 to 170 ft/hr. The instantaneous ROP can reach in excess of 500 ft/hr. The original bit used did not consistently achieve those goals and suffered from regular damage to blade 1 cutter 1 (Fig. 15, left).

Figure 15—left, offset bit showing diamond table delamination on blade 1 cutter 1; right, the new bit pulled out green

Using the bit simulator, we were able to identify that the cutter in question had a significant amount of rubbing with the formation, on its substrate, and on the inside of the cutter interface (Fig. 16, left). For the new design, we adjusted the cutter size and position in such a way that it did not contact the formation near the face of the cutter, and that the cutter substrate had reduced rubbing (Fig. 16, right). The new bit achieved the desired goal: it drilled 15,564 feet at an average ROP of 147 ft/hr, showing no damage to the cutter (Fig. 15, right).

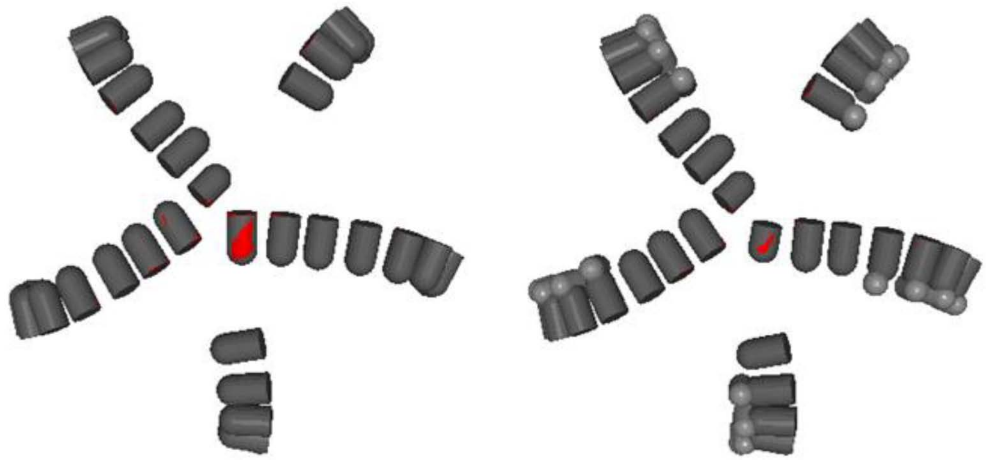

Figure 16—left, offset bit design showing a significant amount of rubbing; right, the new bit design with reduced rubbing

Case study #3 – challenging extreme ROP (Canada)

In high ROP (large depth of cut) drilling applications, determining cutter placement and cutter exposure is critical during the bit design phase to achieve the desired bit performance. In Southern Saskatchewan, Canada, instantaneous ROP can be as high as 1000 ft/hr (300 m/hr). On average, the 222mm diameter hole section begins at 200m TVD ends at KOP at 1200m TVD drilling on average 1000m vertically. With the use of the bit simulator, a fresh new bit had been designed and virtually run through a series of different drilling parameters to determine if and where the formation would contact the body of the PDC. Fig. 17 (left) shows where blade tops contacts develop as indicated by red striping.

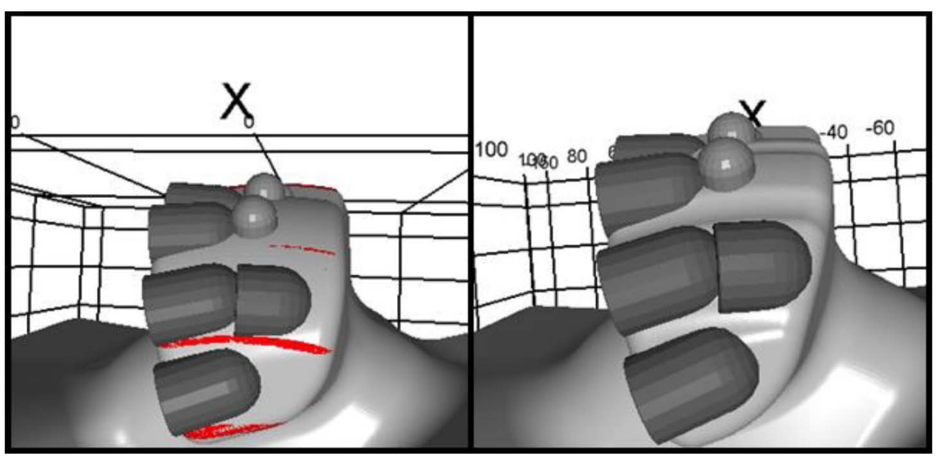

Figure 17—blade top striping on the initial design (left) and on the final design (right)

With this knowledge at hand, we have been able to modify this design by modelling some striping directly built into the body of the bit (Fig. 17, right). Then the new bit design has been run through the simulator, to verify the design, the cutter chip generation, the depth of cut on each cutter and formation contacts on cutters and blades to eliminate formation contact which ultimately slows the bit. With less formation contacting the bit body, the energy provided to the drill bit is used to shear and remove the formation rather than generate heat and damage to the drill bit. This simulation work significantly increases bit advancement without prototype bits ever having to get test runs in the field. Fig. 18 shows the final bit design which was run in the field and achieved an average ROP of 150 m/hr with instantaneous peaks of 300 m/hr.

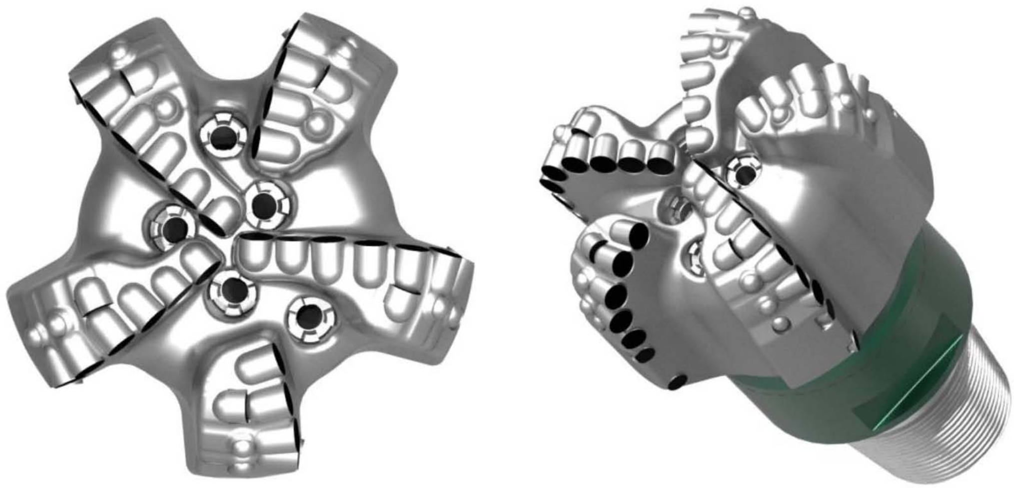

Figure 18—final design of the 8.75" R516PDUX with built-in striping on the bit body

Conclusion

In this paper, a 3D PDC drill bit simulator has been presented. It simulates the rock removal process and the occurrence of contacts between the rock formation and the CAD model of the drill bit. It also allows to estimate bit performance, balancing, steerability and tool face control.

The geometric model of the simulator is based on the computational geometry library CGAL which offers powerful tools to ensure computational accuracy, robustness and rapidity. A significant track record of post-run analyses shows that the prediction of rubbing areas closely match field observations.

Several case studies originating from US shale plays and Canada have been presented to demonstrate the benefit of conducting bit design analyses in a full 3D framework. Non-standard bit design issues have been solved with the help of the simulator and have led to an overall increase in bit performance and durability.

The 3D PDC drill bit simulator is fully operational and used daily by application engineers to optimize bit designs. Moreover, the generic approach which has been followed leaves the gate open to future developments: modelling new drilling environments; extending the validity of implemented physical models based on dedicated drilling bench experiments or coupling this drill bit simulator to a drill string simulator.

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