**UNITED STATES DISTRICT COURT FOR
THE EASTERN DISTRICT OF TEXAS
SHERMAN DIVISION**

HALLIBURTON ENERGY SERVICES, INC.	)	
a Delaware Corporation	)	
	)	
Plaintiff,	)	**CIVIL ACTION NO.** 4:02cv269
	)	
v.	)	
	)	**Jury Trial Demanded**
SMITH INTERNATIONAL, INC.	)	Judge Brown
a Delaware Corporation,	)	
	)	
Defendant.	)	

PLAINTIFF'S ORIGINAL COMPLAINT FOR PATENT INFRINGEMENT AND JURY DEMAND

For its complaint herein, Plaintiff HALLIBURTON ENERGY SERVICES, INC. avers as follows:

1 Plaintiff, HALLIBURTON ENERGY SERVICES, INC., is a corporation organized and existing under the laws of the State of Delaware with a place of business at 3400 West Illinois Avenue, Dallas, Texas 75211-0600.

2. Defendant, SMITH INTERNATIONAL, INC., is a corporation organized and existing under the laws of the State of Delaware with a place of business at 16740 Hardy Street, Houston, Texas 77205.

3. This is an action arising under the Patent Laws of the United States, United States Code, Title 35. Jurisdiction and venue are predicated upon United States Code, Title 28, §§1331, 1332, 1338, 1391 and 1400. On information and belief, the Defendant has committed acts of infringement in this district and/or has a place of business in this district.

4. Plaintiff is widely recognized in the oil and gas industry as an innovator and provider of high quality drill bits. Drill bits are commonly used throughout the industry by drilling operators for oil and gas production.

5. Plaintiff invented a revolutionary new type of roller cone drill bit known as Energy Balanced Bits.

6. Plaintiff filed patent applications and received several United States Letters Patents for its Energy Balanced Bits. Attached to this complaint as Exhibits A1-A4 are copies of Plaintiff's United States Letters Patents which include the following:

- United States Letters Patent No. 6,095,262 dated August 1, 2002, with a filing date of August 31, 1999, and having a priority date of August 31, 1998;
- United States Letters Patent No. 6,213,225 dated April 10, 2001, with a filing date August 31, 1999, and having a priority date of August 31, 1998;
- United States Letters Patent No. 6,401,839 dated June 11, 2002, with a filing date of March 10, 2000, and having a priority date of August 31, 1998;
- United States Letters Patent No. 6,412,577 dated July 2, 2002, with a filing date of August 1, 2002, and having a priority date of August 31, 1998 ("Plaintiff's Patents").

7. Plaintiff is and has continuously been the owner of all right, title and interest in and to Plaintiff's Patents.

8. Upon information and belief, Defendant is making, using and selling, within this District and elsewhere, "Twist and Shout" drill bits, which infringe Plaintiff's Patents. Upon information and belief, Defendant is using a process, within this District and elsewhere, known as the "Integrated Dynamic Engineering Analysis System" to design and manufacture its drill bits

that infringe Plaintiff's Patents and, as such, Defendant's process likewise infringes Plaintiff's Patents.

9. Defendant is infringing Plaintiff's Patents willfully and with knowledge of at least one or more of Plaintiff's Patents.

10. As a result of Defendant's infringement, Plaintiff has suffered and will continue to suffer grievous damage.

11. Defendant's infringement of Plaintiff's Patents will continue unless and until enjoined by this Court.

WHEREFORE Plaintiff prays that this Court enter judgment:

1. Enjoining Defendant and its subsidiaries, agents, officers and employees, and all others acting in concert with it, from the manufacture, use, design, offer for sale and sale of drill bits and methods of manufacturing drill bits which infringe United States Letters Patent No. 6,095,262, Patent No. 6,213,225, Patent No. 6,412,577 and Patent No. 6,401,839.

2. Order Defendant to account for its profits and damages, including those arising out of Defendant's willful conduct, to Plaintiff from such infringement.

3. Assessing costs and interest, including attorneys' fees, against Defendant.

4. Granting Plaintiff such other and further relief as is just.

JURY DEMAND

Plaintiff hereby requests a trial by jury of all issues so triable.

DATED: 9/6/02

Respectfully submitted,

By: [signature]

Arthur I. Navarro
Texas Bar No. 00792013
Donald E. Godwin
Texas Bar No. 08056500
David L. Patterson
Texas Bar No. 15587400

GODWIN GRUBER, P.C.
1201 Elm Street, Suite 1700
Dallas, Texas 75270

ATTORNEYS FOR PLAINTIFF
HALLIBURTON ENERGY SERVICES, INC.

OF COUNSEL:
Joseph W. Wolfe
Texas Bar No. 21859000
Wolfe, Clark, Henderson, Tidwell & McCoy, L.L.P.
123 North Crockett Street, Suite 100
Sherman, Texas 75090

William R. Peoples
Texas Bar No. 15766250
Halliburton Energy Services, Inc.
2601 Beltline Road, 1B-121-1
Carrollton, Texas 75006-5401

US006095262A

United States Patent [19]

Chen

[11] Patent Number: 6,095,262

[45] Date of Patent: Aug. 1, 2000

[54] ROLLER-CONE BITS, SYSTEMS, DRILLING METHODS, AND DESIGN METHODS WITH OPTIMIZATION OF TOOTH ORIENTATION

[75] Inventor: Shilin Chen, Dallas, Tex.

[73] Assignee: Halliburton Energy Services, Inc., Carrollton, Tex.

[21] Appl. No.: 09/387,304

[22] Filed: Aug. 31, 1999

Related U.S. Application Data

[60] Provisional application No. 60/098,442, Aug. 31, 1998.

[51] Int. Cl.⁷ E21B 10/16

[52] U.S. Cl. 175/57; 76/108.2; 175/374; 175/376; 175/378

[58] Field of Search 175/57, 331, 374, 175/376, 377, 378; 76/108.2, 108.4

[56] References Cited

U.S. PATENT DOCUMENTS

4,187,922	2/1980	Phelps	175/374
4,393,948	7/1983	Fernandez	175/374
4,427,081	1/1984	Crawford	175/376
4,815,342	3/1989	Brett et al.	76/108.2
5,197,555	3/1993	Estes	175/431
5,372,210	12/1994	Harrell	175/431
5,415,030	5/1995	Jogi et al.	73/152.03
5,704,436	1/1998	Smith et al.	175/27
5,730,234	3/1998	Putot	175/30
5,767,399	6/1998	Smith et al.	73/152.11
5,794,720	8/1998	Smith et al.	175/40

FOREIGN PATENT DOCUMENTS

2241266A 8/1991 United Kingdom .

Primary Examiner—Hoang Dang
Attorney, Agent, or Firm—Groover & Associates

[57] ABSTRACT

A novel and improved roller cone drill bit and method of design are disclosed. A roller cone drill bit for drilling through subterranean formations having an upper connection for attachment to a drill string, and a plurality cutting structures rotatably mounted on arms extending downward from the connection. A number of teeth are located in generally concentric rows on each cutting structure. The actual trajectory by which the teeth engage the formation is mathematically determined. A straight-line trajectory is calculated based on the actual trajectory. The teeth are positioned in the cutting structures such each tooth having a designed engagement surface is oriented perpendicular to the calculated straight-line trajectory.

21 Claims, 21 Drawing Sheets

ERA22_V Cone No.1

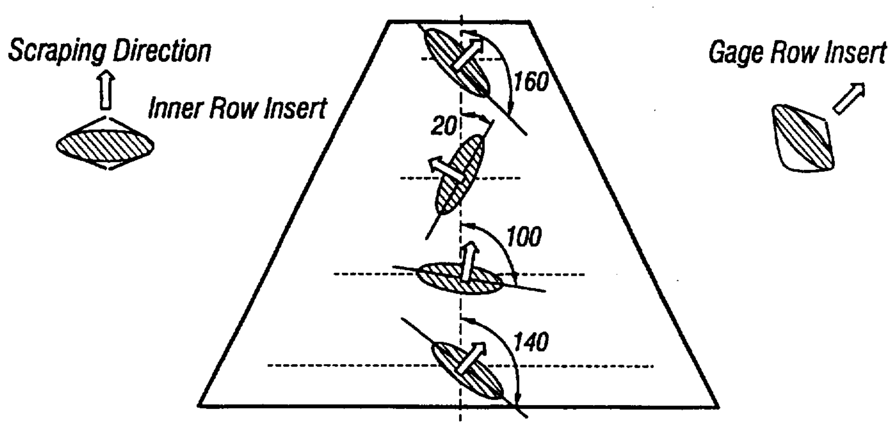


EXHIBIT A1

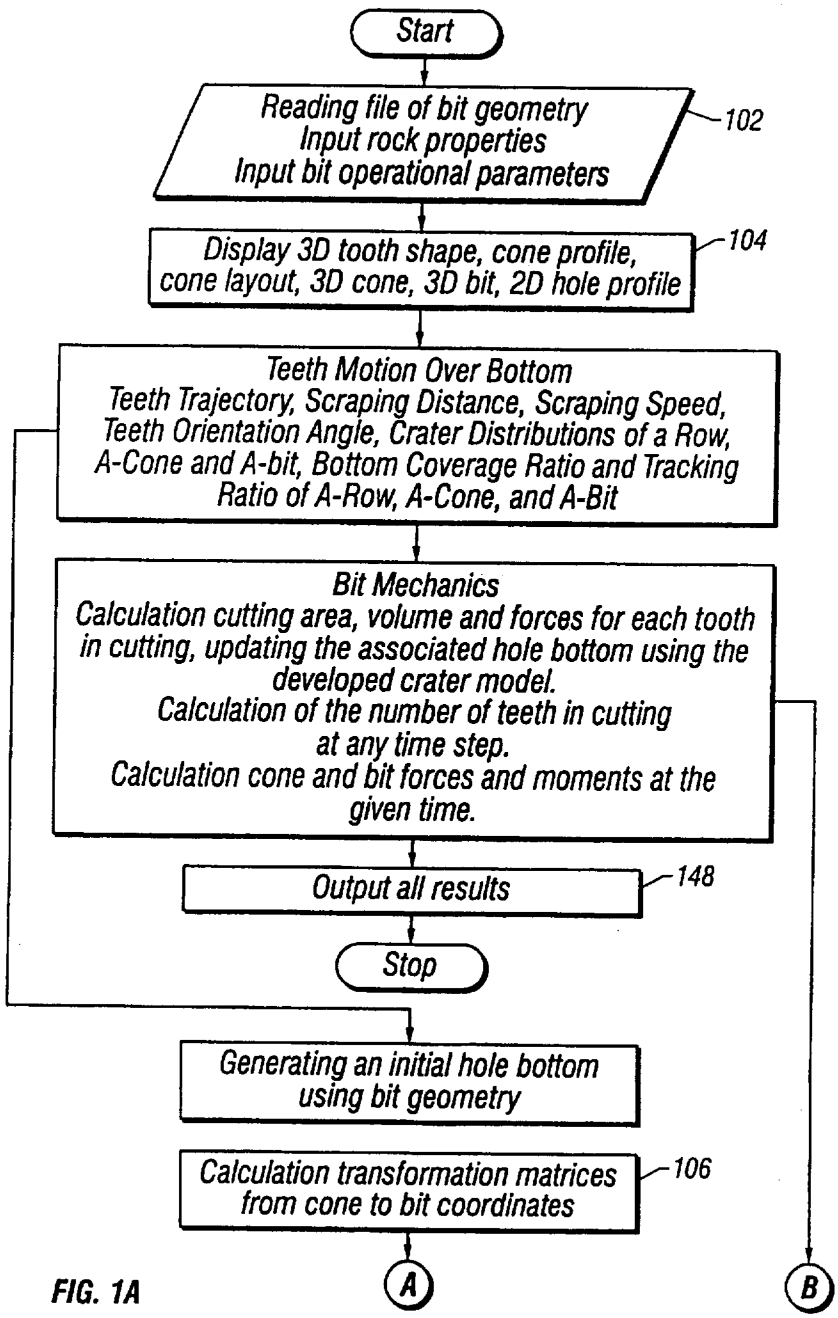

Start
Reading file of bit geometry
Input rock properties
Input bit operational parameters
102
Display 3D tooth shape, cone profile, cone layout, 3D cone, 3D bit, 2D hole profile
104
Teeth Motion Over Bottom
Teeth Trajectory, Scraping Distance, Scraping Speed, Teeth Orientation Angle, Crater Distributions of a Row, A-Cone and A-bit, Bottom Coverage Ratio and Tracking Ratio of A-Row, A-Cone, and A-Bit
Bit Mechanics
Calculation cutting area, volume and forces for each tooth in cutting, updating the associated hole bottom using the developed crater model.
Calculation of the number of teeth in cutting at any time step.
Calculation cone and bit forces and moments at the given time.
Output all results
148
Stop
Generating an initial hole bottom using bit geometry
Calculation transformation matrices from cone to bit coordinates
106
A
B

FIG. 1A

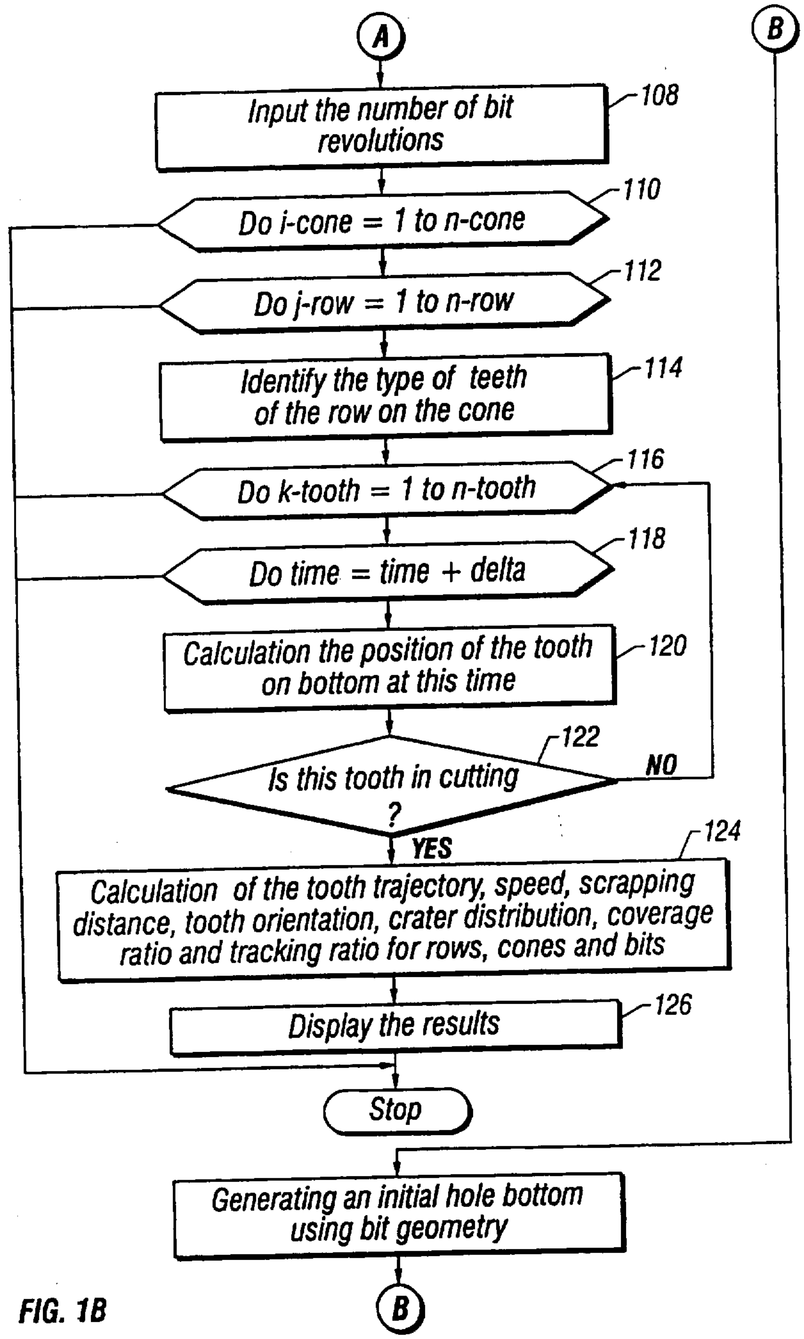

A
B
Input the number of bit revolutions
108
Do i-cone = 1 to n-cone
110
Do j-row = 1 to n-row
112
Identify the type of teeth of the row on the cone
114
Do k-tooth = 1 to n-tooth
116
Do time = time + delta
118
Calculation the position of the tooth on bottom at this time
120
Is this tooth in cutting ?
122
NO
YES
Calculation of the tooth trajectory, speed, scrapping distance, tooth orientation, crater distribution, coverage ratio and tracking ratio for rows, cones and bits
124
Display the results
126
Stop
Generating an initial hole bottom using bit geometry
B

FIG. 1B

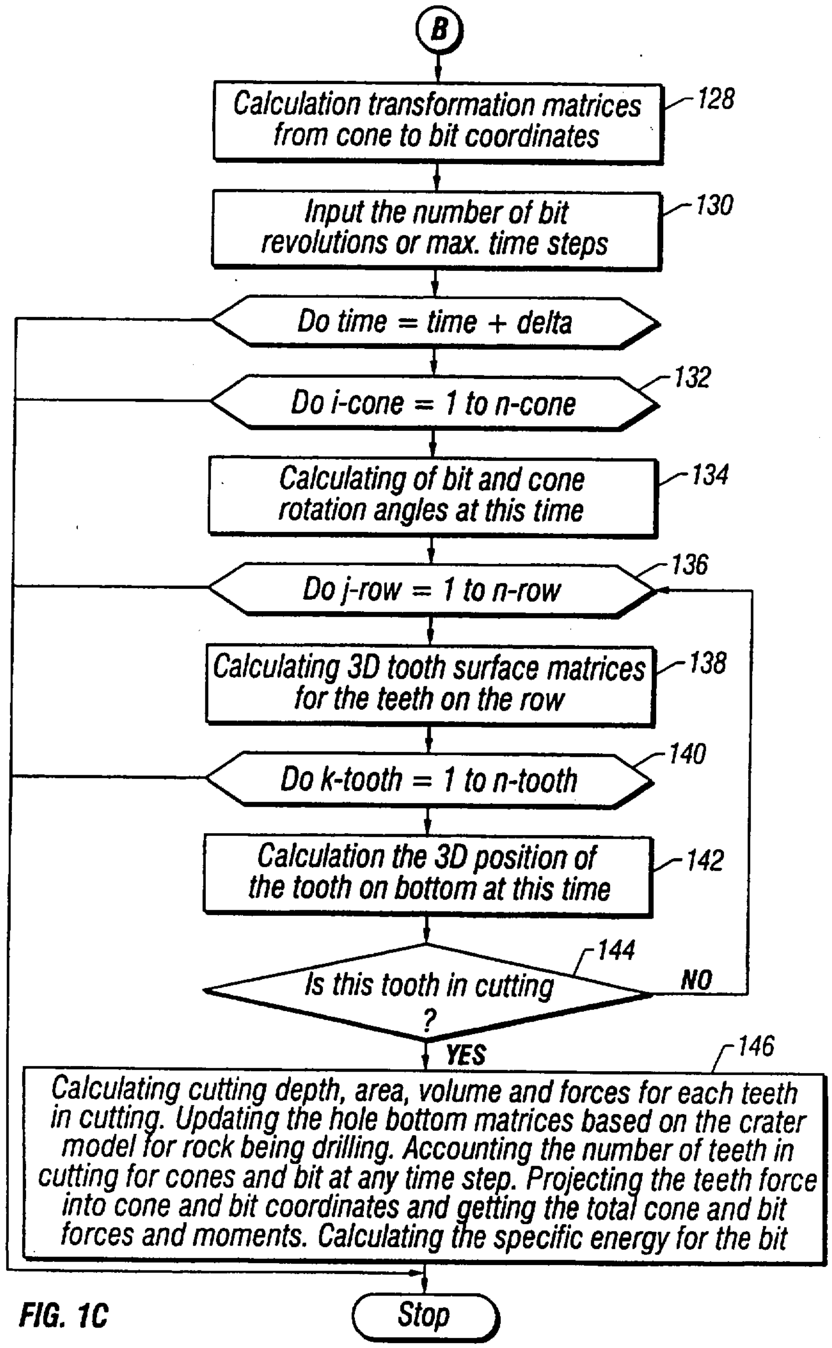

B
Calculation transformation matrices from cone to bit coordinates
128
Input the number of bit revolutions or max. time steps
130
Do time = time + delta
Do i-cone = 1 to n-cone
132
Calculating of bit and cone rotation angles at this time
134
Do j-row = 1 to n-row
136
Calculating 3D tooth surface matrices for the teeth on the row
138
Do k-tooth = 1 to n-tooth
140
Calculation the 3D position of the tooth on bottom at this time
142
Is this tooth in cutting ?
144
NO
YES
146
Calculating cutting depth, area, volume and forces for each teeth in cutting. Updating the hole bottom matrices based on the crater model for rock being drilling. Accounting the number of teeth in cutting for cones and bit at any time step. Projecting the teeth force into cone and bit coordinates and getting the total cone and bit forces and moments. Calculating the specific energy for the bit
Stop

FIG. 1C

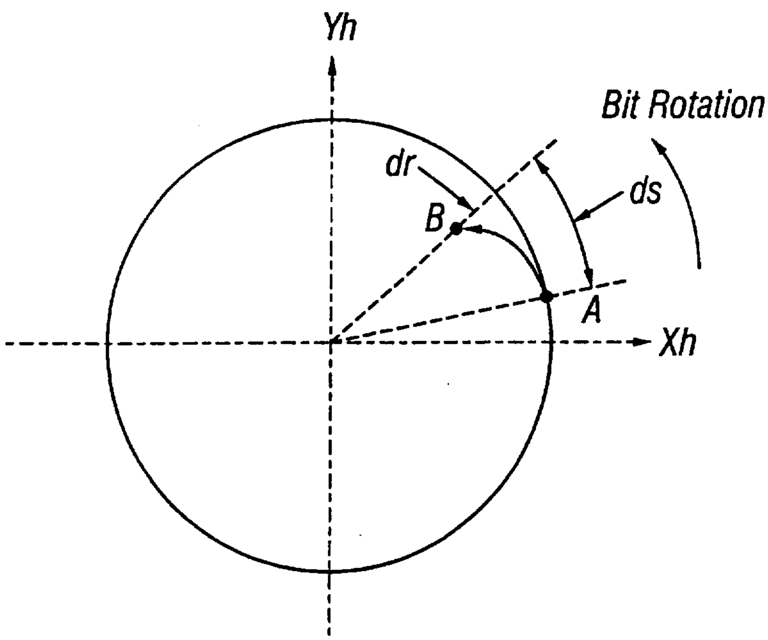


FIG. 2

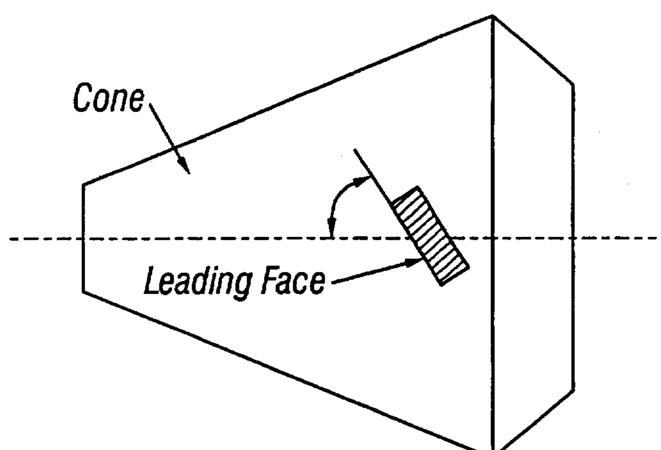


FIG. 5

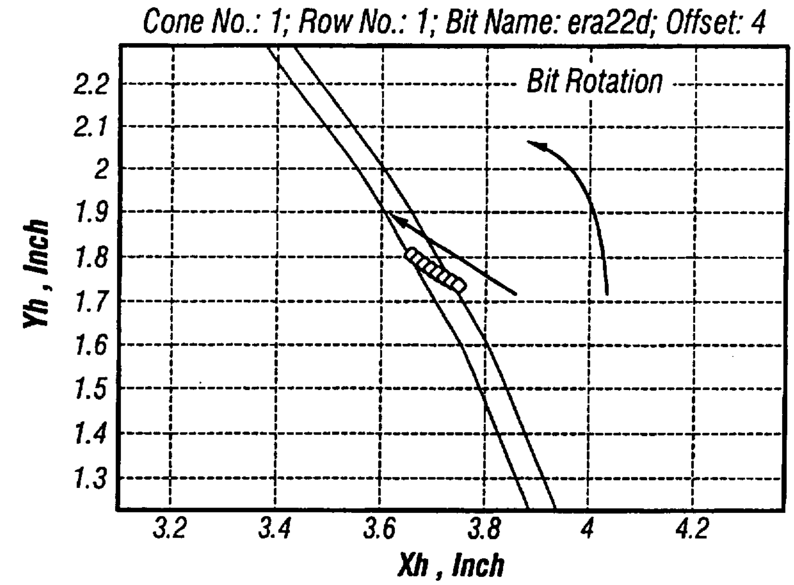

Cone No.: 1; Row No.: 1; Bit Name: era22d; Offset: 4
Bit Rotation
Yh , Inch
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
3.2
3.4
3.6
3.8
4
4.2
Xh , Inch

FIG. 3A

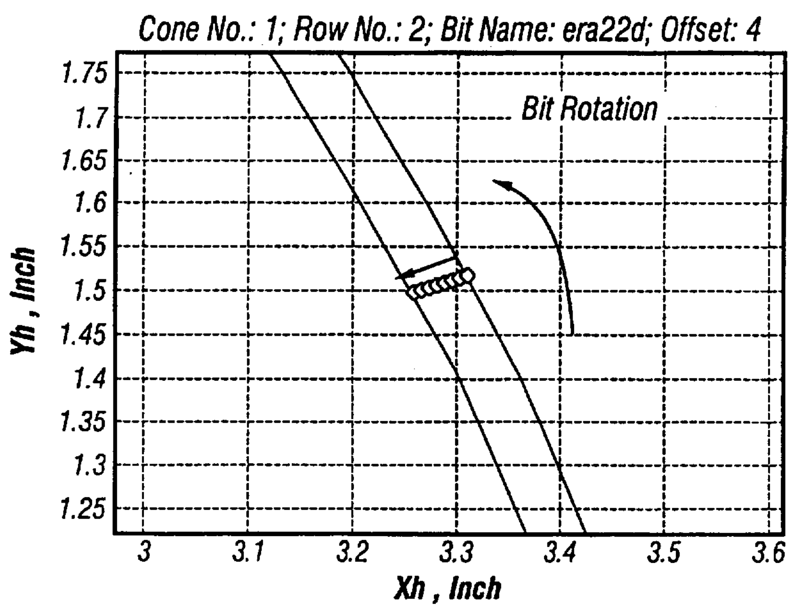
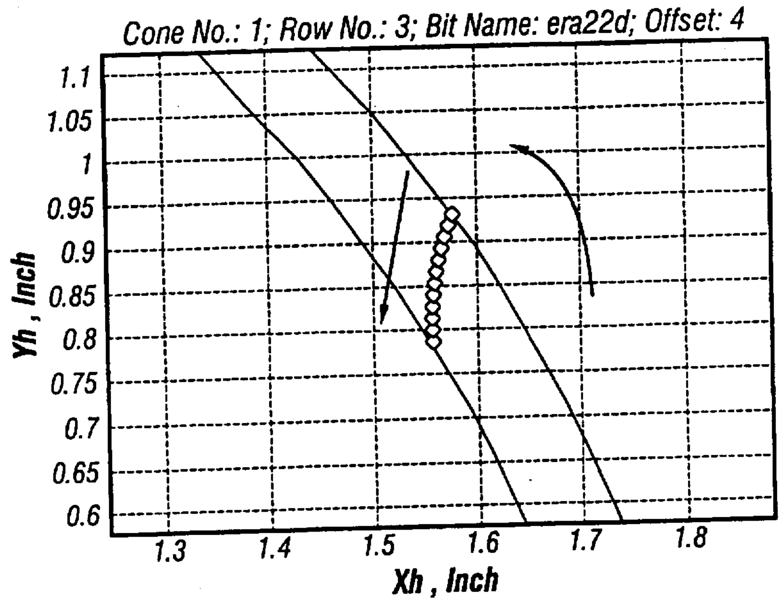
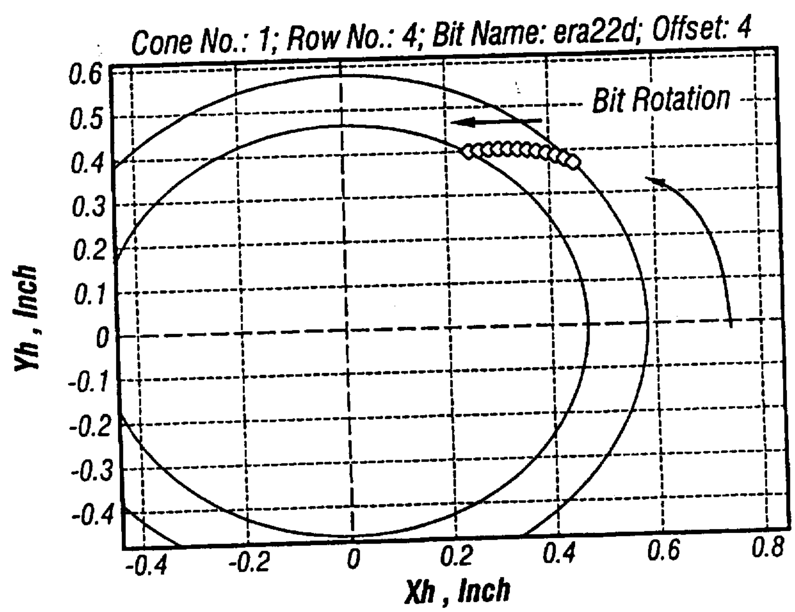

Cone No.: 1; Row No.: 2; Bit Name: era22d; Offset: 4
Bit Rotation
Yh , Inch
1.75
1.7
1.65
1.6
1.55
1.5
1.45
1.4
1.35
1.3
1.25
3
3.1
3.2
3.3
3.4
3.5
3.6
Xh , Inch

FIG. 3B



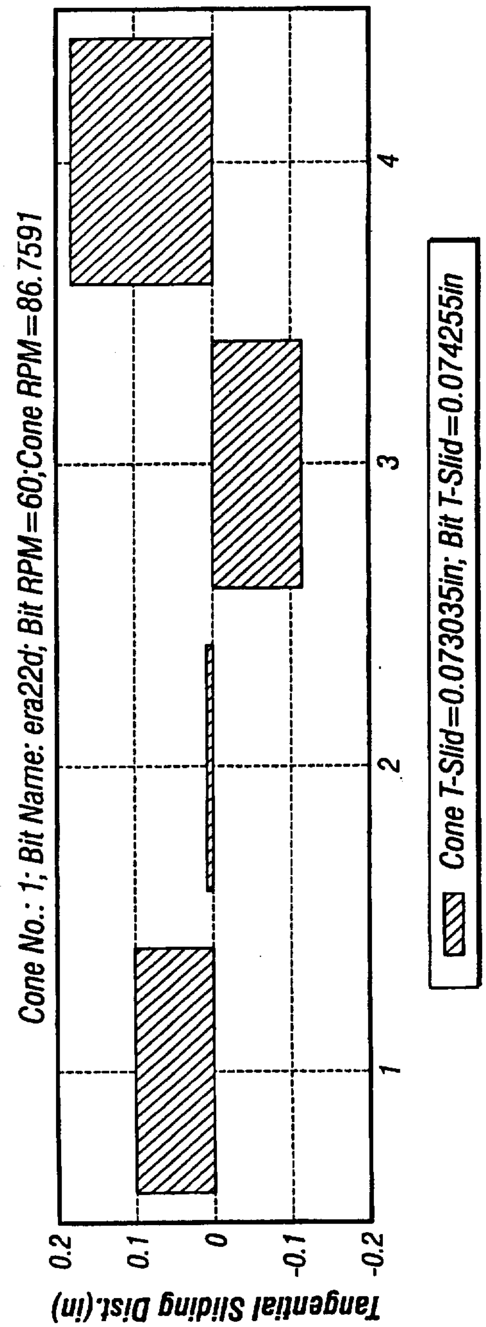
Cone No.: 1; Row No.: 3; Bit Name: era22d; Offset: 4
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Yh , Inch
1.3
1.4
1.5
1.6
1.7
1.8
Xh , Inch

FIG. 3C



Cone No.: 1; Row No.: 4; Bit Name: era22d; Offset: 4
Bit Rotation
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Yh , Inch
-0.4
-0.2
0
0.2
0.4
0.6
0.8
Xh , Inch

FIG. 3D



Cone No.: 1; Bit Name: era222d; Bit RPM=60;Cone RPM=86.7591
Tangential Sliding Dist.(in)
0.2
0.1
0
-0.1
-0.2
1
2
3
4
Cone T-Slid=0.073035in; Bit T-Slid=0.074255in

FIG. 4A

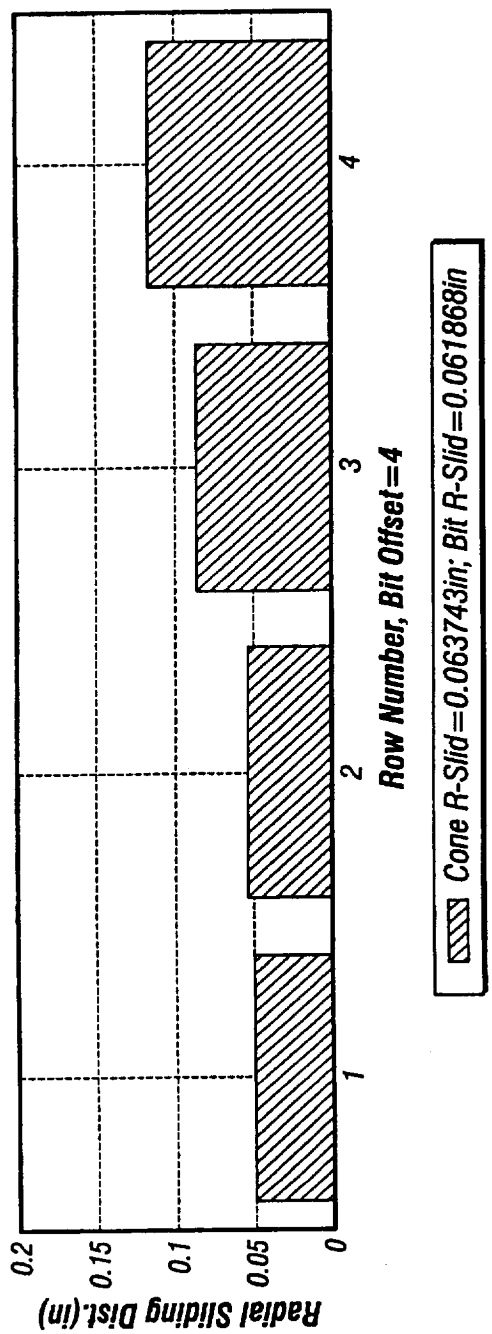

Radial Sliding Dist.(in)
0.2
0.15
0.1
0.05
0
1
2
3
4
Row Number, Bit Offset=4
Cone R-Slid=0.063743in; Bit R-Slid=0.061868in

FIG. 4B

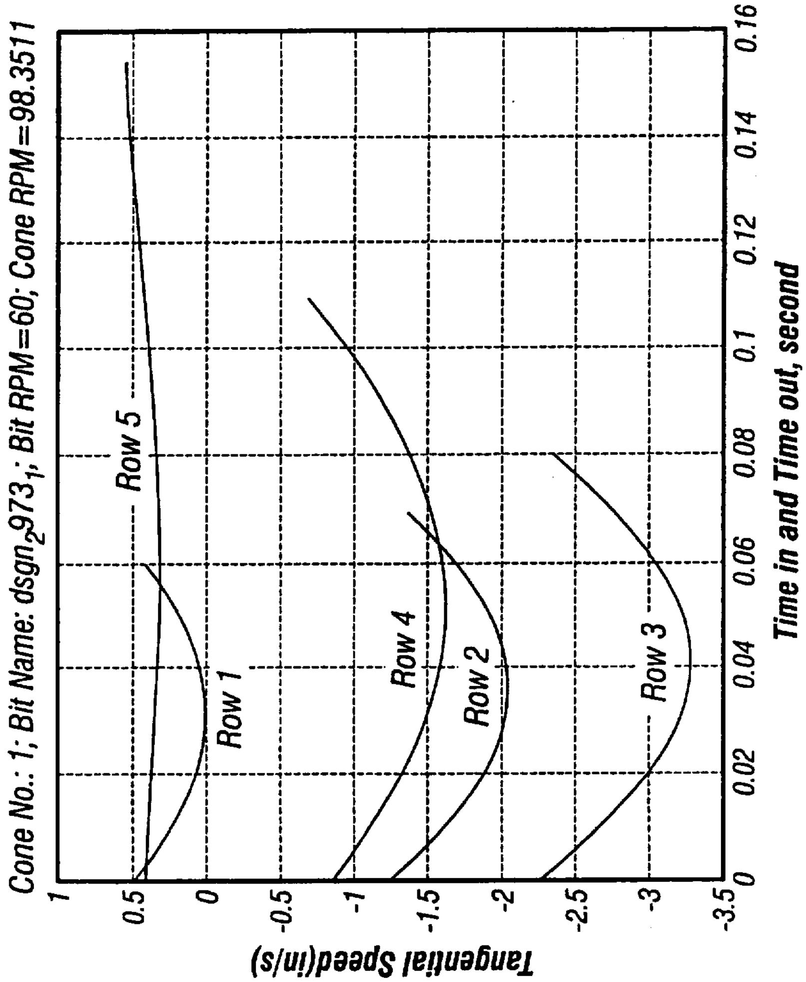
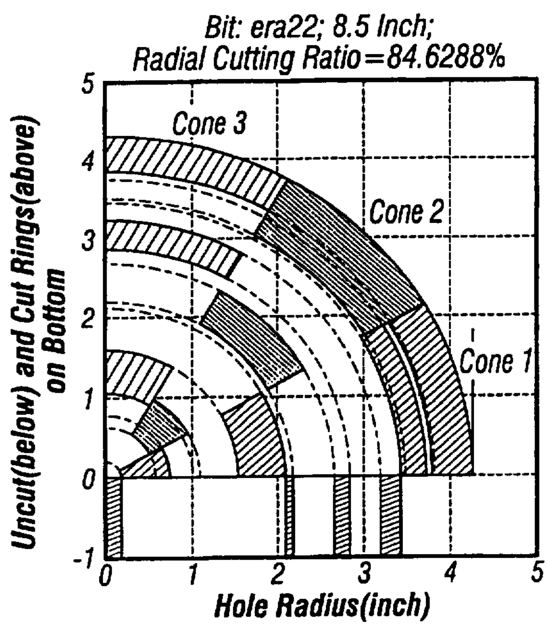
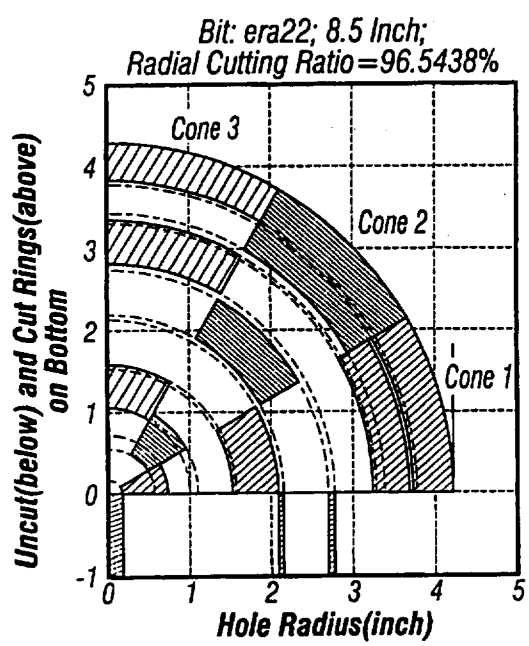

Cone No.: 1; Bit Name: dsgn2973_1; Bit RPM=60; Cone RPM=98.3511
Tangential Speed(in/s)
Time in and Time out, second
Row 1
Row 2
Row 3
Row 4
Row 5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16

FIG. 6



Bit: era22; 8.5 Inch;
Radial Cutting Ratio=84.6288%
Cone 3
Cone 2
Cone 1
Uncut(below) and Cut Rings(above) on Bottom
Hole Radius(inch)
5
4
3
2
1
0
-1
0
1
2
3
4
5

FIG. 7A



Bit: era22; 8.5 Inch;
Radial Cutting Ratio=96.5438%
Cone 3
Cone 2
Cone 1
Uncut(below) and Cut Rings(above) on Bottom
Hole Radius(inch)
5
4
3
2
1
0
-1
0
1
2
3
4
5

FIG. 7B

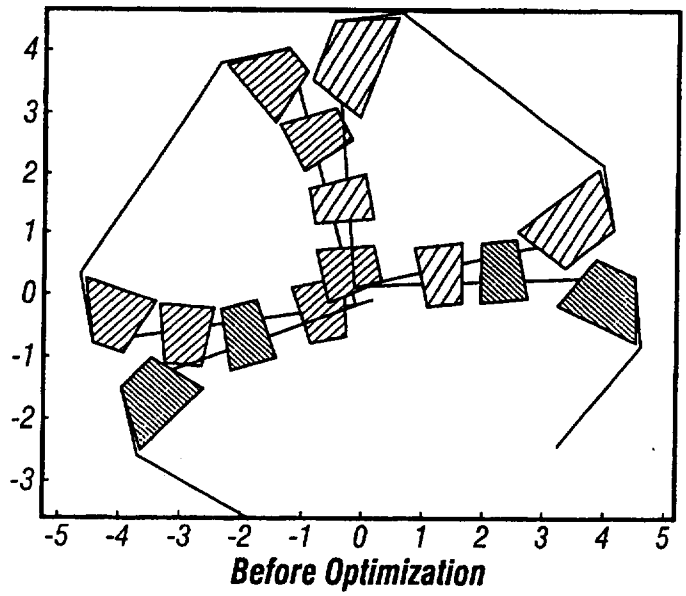

4
3
2
1
0
-1
-2
-3
-5 -4 -3 -2 -1 0 1 2 3 4 5
Before Optimization

FIG. 8A

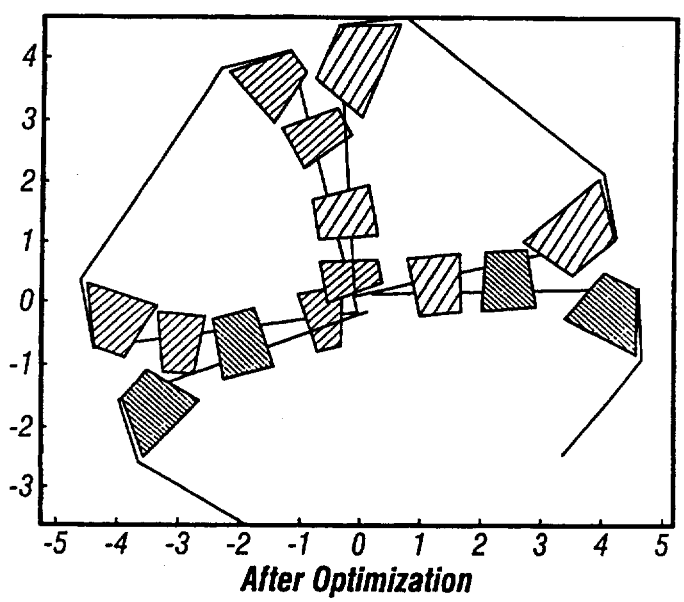

4
3
2
1
0
-1
-2
-3
-5 -4 -3 -2 -1 0 1 2 3 4 5
After Optimization

FIG. 8B

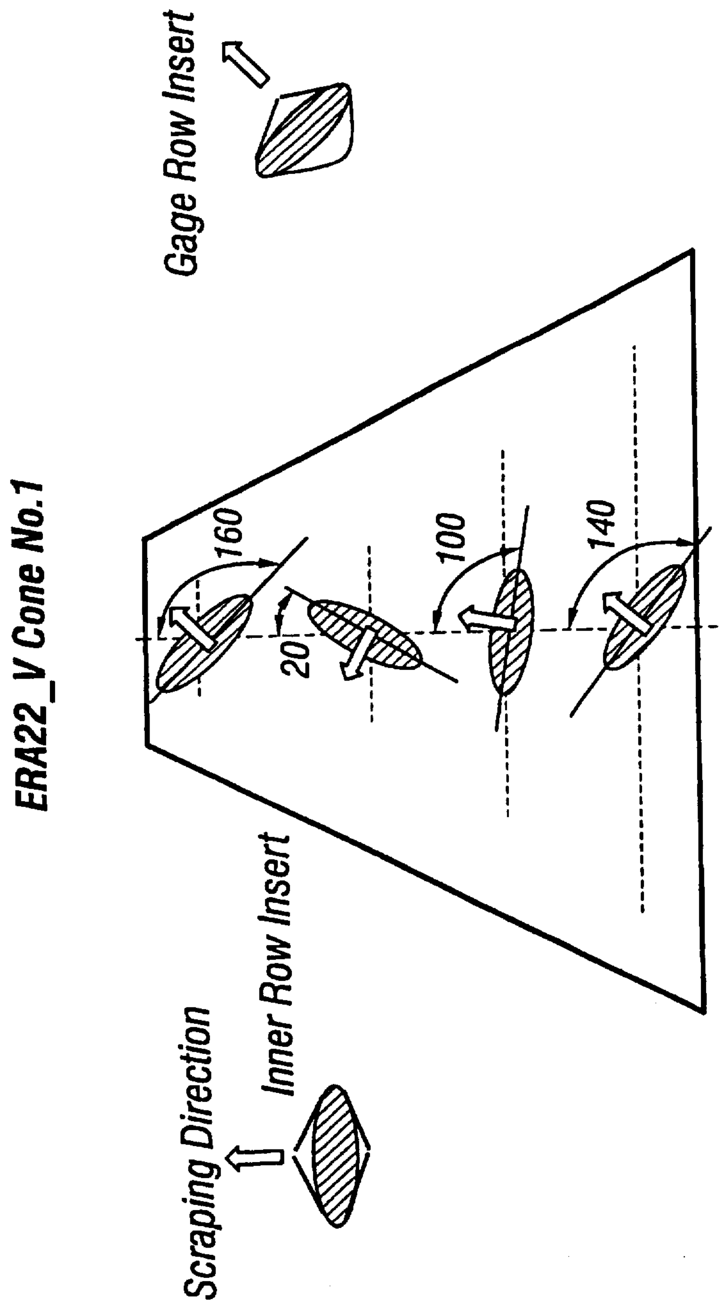

ERA22_V Cone No.1
Gage Row Insert
Inner Row Insert
Scraping Direction
160
20
100
140

FIG. 9A

ERA22_V Cone No.2

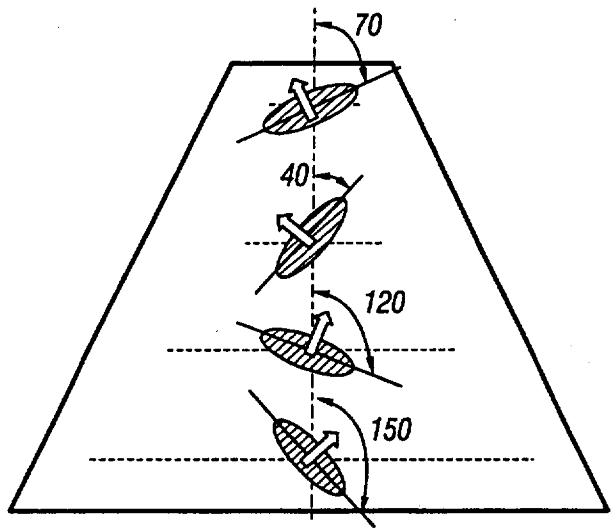


FIG. 9B

ERA22_V Cone No.3

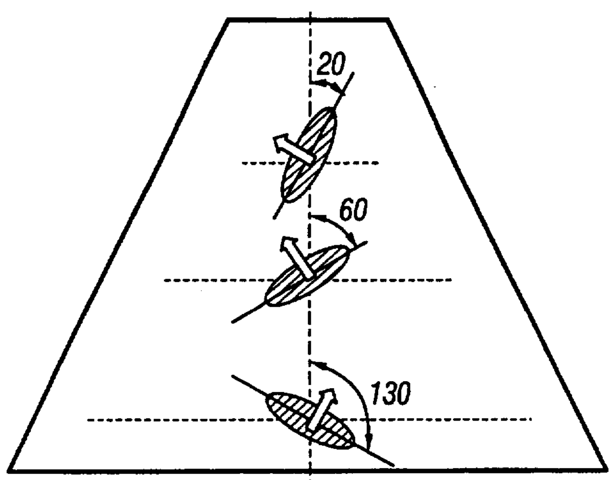


FIG. 9C

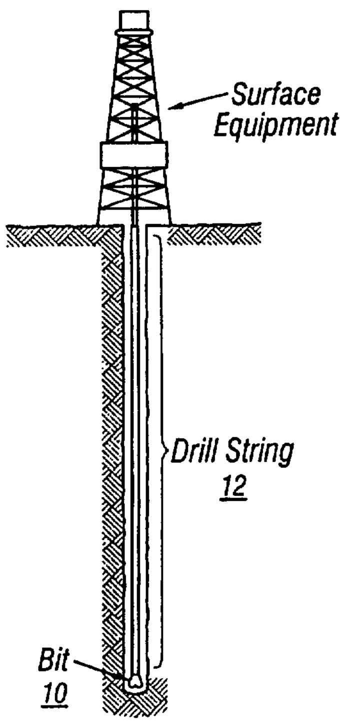


FIG. 10

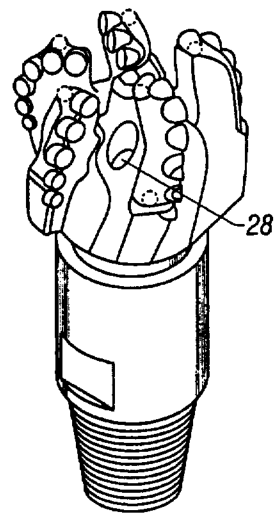


FIG. 11

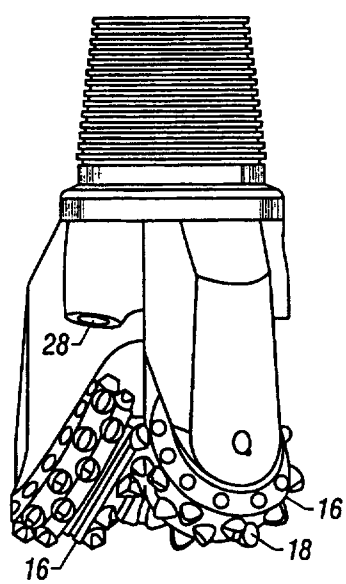


FIG. 12

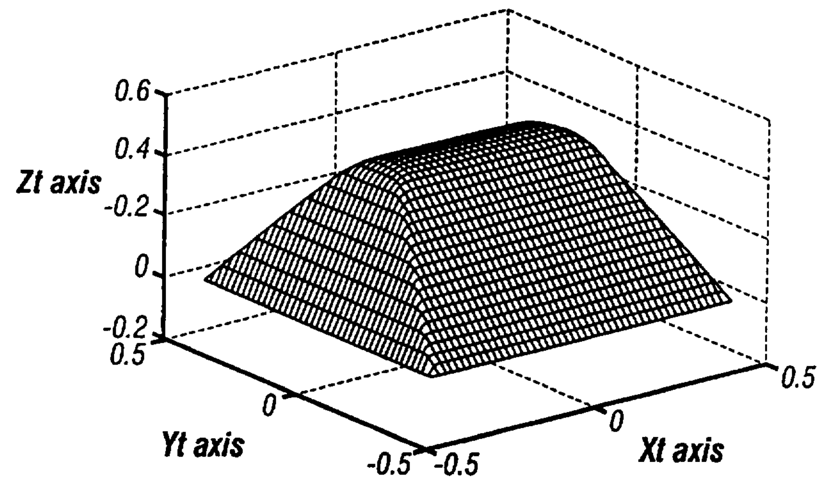

0.6
0.4
Zt axis
-0.2
0
-0.2
0.5
0
Yt axis
-0.5
-0.5
0
Xt axis
0.5

FIG. 13

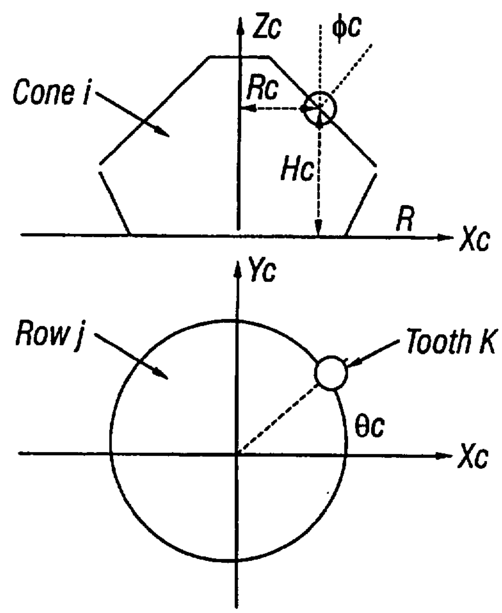

Zc
φc
Cone i
Rc
Hc
R
Xc
Yc
Row j
Tooth K
θc
Xc

FIG. 14

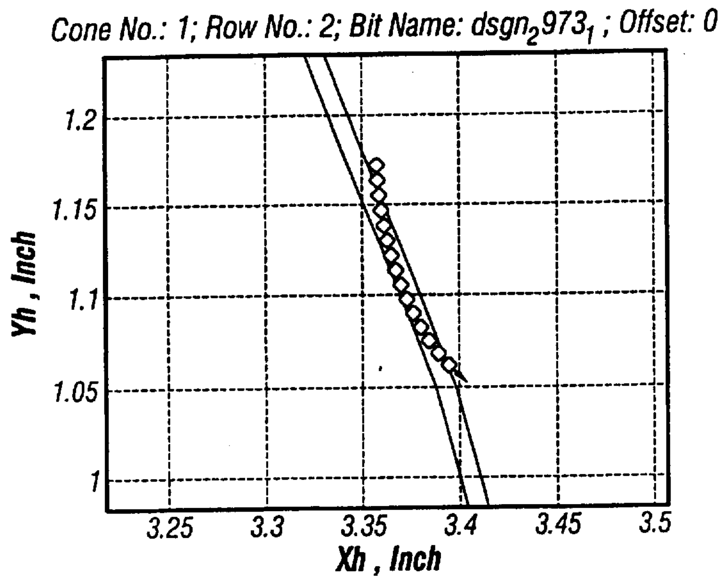


FIG. 15A

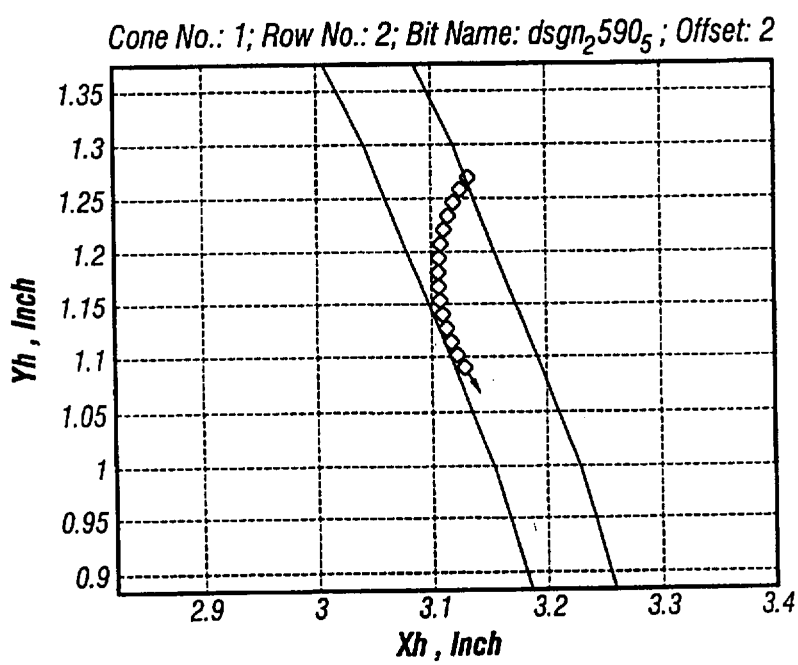


FIG. 15B

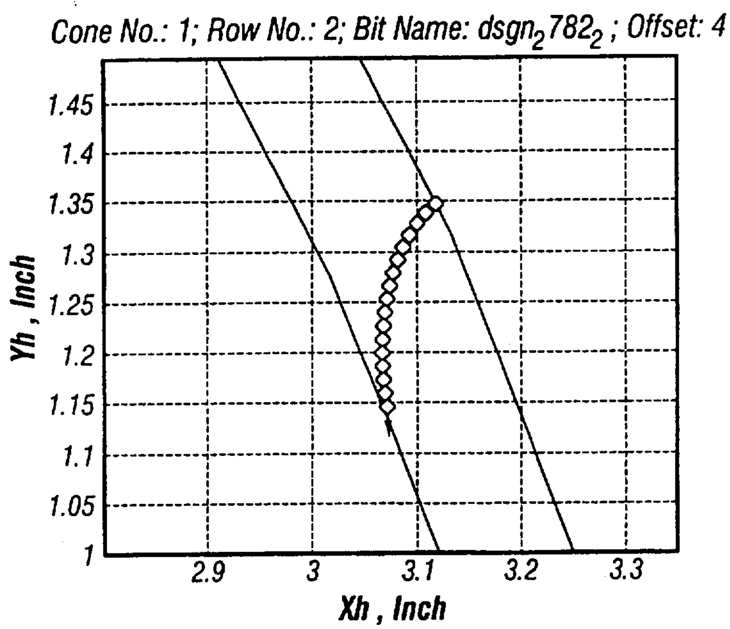


FIG. 15C

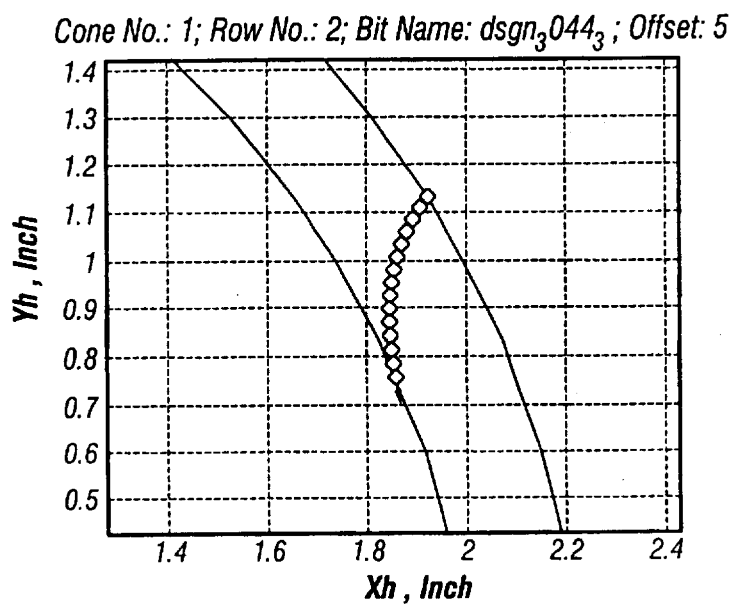


FIG. 15D

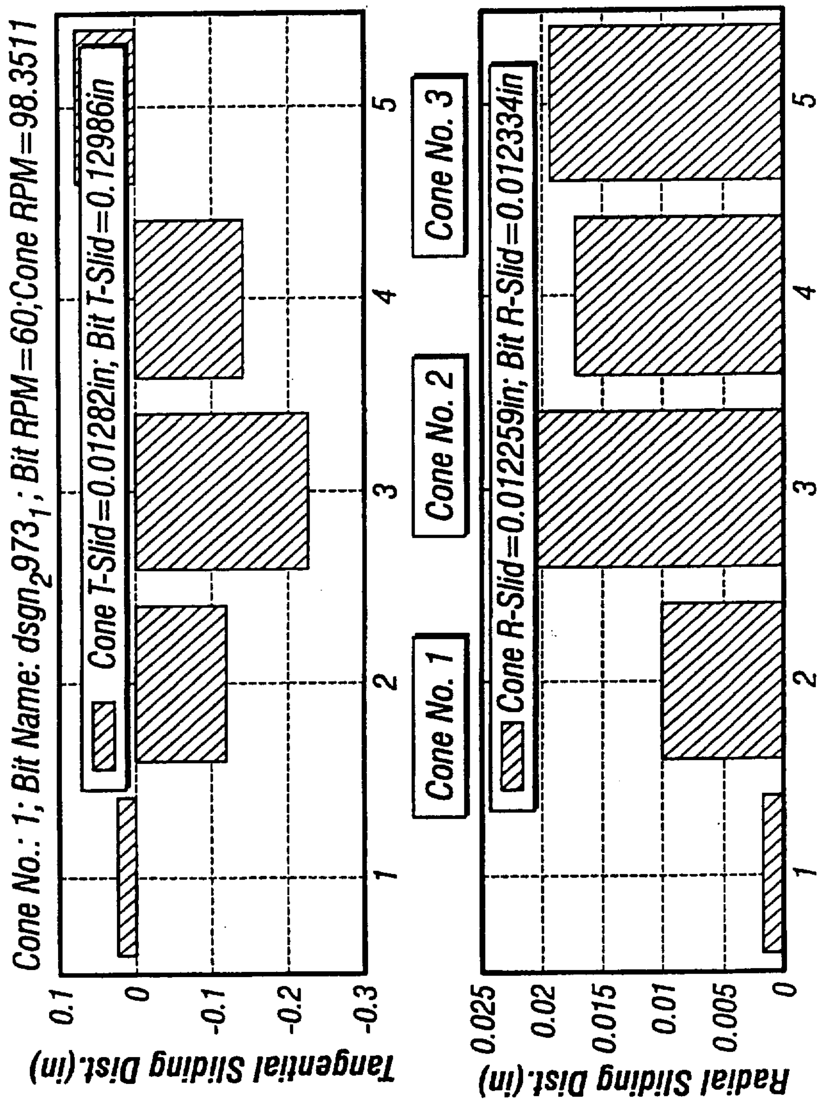

Cone No.: 1; Bit Name: dsgn2973 1; Bit RPM=60;Cone RPM=98.3511
Cone T-Slid=0.01282in; Bit T-Slid=0.12986in
Tangential Sliding Dist.(in)
0.1
0
-0.1
-0.2
-0.3
1
2
3
4
5
Cone No. 1
Cone No. 2
Cone No. 3
Cone R-Slid=0.012259in; Bit R-Slid=0.012334in
Radial Sliding Dist.(in)
0.025
0.02
0.015
0.01
0.005
0

FIG. 16A

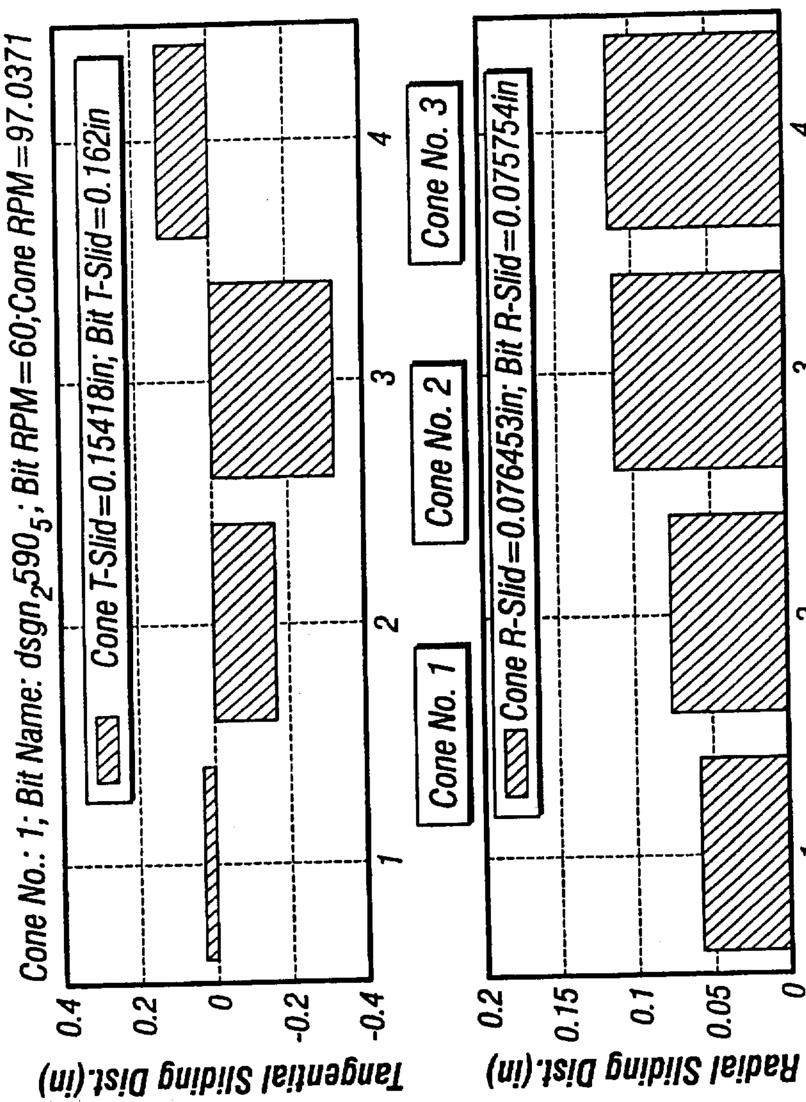

Cone No.: 1; Bit Name: dsgn2590 5; Bit RPM=60;Cone RPM=97.0371
Cone T-Slid=0.15418in; Bit T-Slid=0.162in
Tangential Sliding Dist.(in)
0.4
0.2
0
-0.2
-0.4
1
2
3
4
Cone No. 1
Cone No. 2
Cone No. 3
Cone R-Slid=0.076453in; Bit R-Slid=0.075754in
Radial Sliding Dist.(in)
0.2
0.15
0.1
0.05
0

FIG. 16B

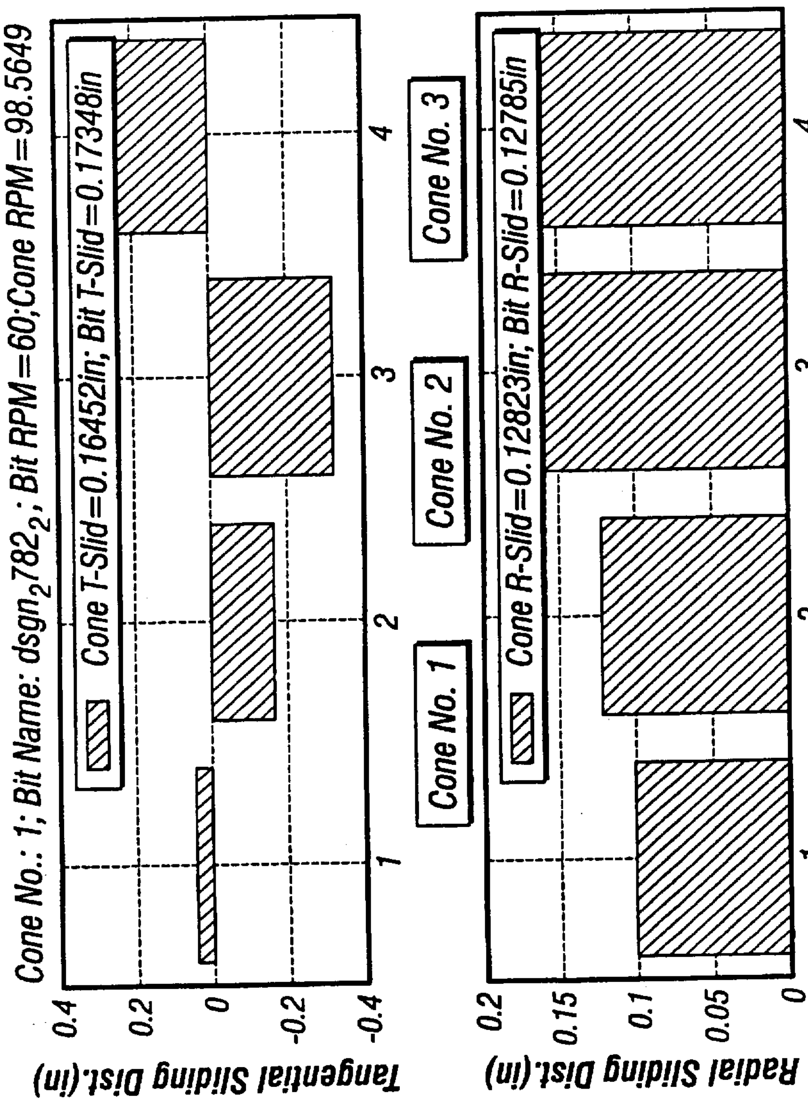

Cone No.: 1; Bit Name: dsgn$_2$782$_2$; Bit RPM=60;Cone RPM=98.5649
Cone T-Slid=0.16452in; Bit T-Slid=0.17348in
Tangential Sliding Dist.(in)
0.4
0.2
0
-0.2
-0.4
1
2
3
4
Cone No. 1
Cone No. 2
Cone No. 3
Cone R-Slid=0.12823in; Bit R-Slid=0.12785in
Radial Sliding Dist.(in)
0.2
0.15
0.1
0.05
0

FIG. 16C

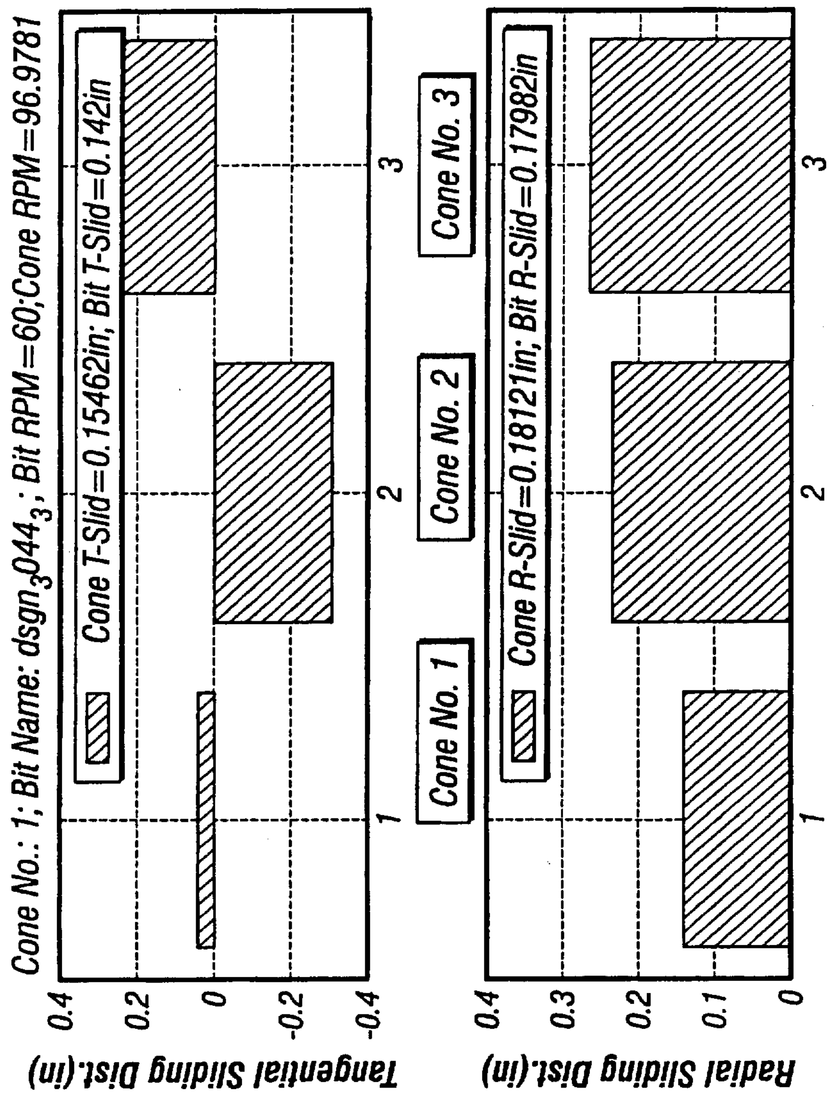

Cone No.: 1; Bit Name: dsgn3044₃; Bit RPM=60;Cone RPM=96.9781
Cone T-Slid=0.15462in; Bit T-Slid=0.142in
Tangential Sliding Dist.(in)
0.4
0.2
0
-0.2
-0.4
Cone No. 1
Cone No. 2
Cone No. 3
1
2
3
Cone R-Slid=0.18121in; Bit R-Slid=0.17982in
Radial Sliding Dist.(in)
0.4
0.3
0.2
0.1
0

FIG. 16D

ROLLER-CONE BITS, SYSTEMS, DRILLING METHODS, AND DESIGN METHODS WITH OPTIMIZATION OF TOOTH ORIENTATION

CROSS-REFERENCE TO OTHER APPLICATION

This application claims priority from 60/098,442 filed Aug. 31, 1998, which is hereby incorporated by reference.

BACKGROUND AND SUMMARY OF THE INVENTION

The present invention relates generally to the drilling of oil and gas wells, or similar drilling operations, and in particular to orientation of tooth angles on a roller cone drill bit.

Background: Rotary Drilling

Oil wells and gas wells are drilled by a process of rotary drilling, using a drill rig such as is shown in FIG. 10. In conventional vertical drilling, a drill bit 10 is mounted on the end of a drill string 12 (drill pipe plus drill collars), which may be more than a mile long, while at the surface a rotary drive (not shown) turns the drill string, including the bit at the bottom of the hole.

Two main types of drill bits are in use, one being the roller cone bit, an example of which is seen in FIG. 11. In this bit a set of cones 16 (two are visible) having teeth or cutting inserts 18 are arranged on rugged bearings on the arms of the bit. As the drill string is rotated, the cones will roll on the bottom of the hole, and the teeth or cutting inserts will crush the formation beneath them. (The broken fragments of rock are swept uphole by the flow of drilling fluid.) The second type of drill bit is a drag bit, having no moving parts, seen in FIG. 12.

Drag bits are becoming increasingly popular for drilling soft and medium formations, but roller cone bits are still very popular, especially for drilling medium and medium-hard rock. There are various types of roller cone bits: insert-type bits, which are normally used for drilling harder formations, will have teeth of tungsten carbide or some other hard material mounted on their cones. As the drill string rotates, and the cones roll along the bottom of the hole, the individual hard teeth will induce compressive failure in the formation.

The bit's teeth must crush or cut rock, with the necessary forces supplied by the "weight on bit" (WOB) which presses the bit down into the rock, and by the torque applied at the rotary drive. While the WOB may in some cases be 100,000 pounds or more, the forces actually seen at the drill bit are not constant: the rock being cut may have harder and softer portions (and may break unevenly), and the drill string itself can oscillate in many different modes. Thus the drill bit must be able to operate for long periods under high stresses in a remote environment.

When the bit wears out or breaks during drilling, it must be brought up out of the hole. This requires a process called "tripping": a heavy hoist pulls the entire drill string out of the hole, in stages of (for example) about ninety feet at a time. After each stage of lifting, one "stand" of pipe is unscrewed and laid aside for reassembly (while the weight of the drill string is temporarily supported by another mechanism). Since the total weight of the drill string may be hundreds of tons, and the length of the drill string may be tens of thousands of feet, this is not a trivial job. One trip can require tens of hours and is a significant expense in the drilling budget. To resume drilling the entire process must be reversed. Thus the bit's durability is very important, to minimize round trips for bit replacement during drilling.

Background: Drill String Oscillation

The individual elements of a drill string appear heavy and rigid. However, in the complete drill string (which can be more than a mile long), the individual elements are quite flexible enough to allow oscillation at frequencies near the rotary speed. In fact, many different modes of oscillation are possible. (A simple demonstration of modes of oscillation can be done by twirling a piece of rope or chain: the rope can be twirled in a flat slow circle, or, at faster speeds, so that it appears to cross itself one or more times.) The drill string is actually a much more complex system than a hanging rope, and can oscillate in many different ways; see WAVE PROPAGATION IN PETROLEUM ENGINEERING, Wilson C. Chin, (1994).

The oscillations are damped somewhat by the drilling mud, or by friction where the drill pipe rubs against the walls, or by the energy absorbed in fracturing the formation: but often these sources of damping are not enough to prevent oscillation. Since these oscillations occur down in the wellbore, they can be hard to detect, but they are generally undesirable. Drill string oscillations change the instantaneous force on the bit, and that means that the bit will not operate as designed. For example, the bit may drill oversize, or off-center, or may wear out much sooner than expected. Oscillations are hard to predict, since different mechanical forces can combine to produce "coupled modes"; the problems of gyration and whirl are an example of this.

Background: Roller Cone Bit Design

The "cones" in a roller cone bit need not be perfectly conical (nor perfectly frustroconical), but often have a slightly swollen axial profile. Moreover, the axes of the cones do not have to intersect the centerline of the borehole. (The angular difference is referred to as the "offset" angle.) Another variable is the angle by which the centerline of the bearings intersects the horizontal plane of the bottom of the hole, and this angle is known as the journal angle. Thus as the drill bit is rotated, the cones typically do not roll true, and a certain amount of gouging and scraping takes place. The gouging and scraping action is complex in nature, and varies in magnitude and direction depending on a number of variables.

Conventional roller cone bits can be divided into two broad categories: Insert bits and steel-tooth bits. Steel tooth bits are utilized most frequently in softer formation drilling, whereas insert bits are utilized most frequently in medium and hard formation drilling.

Steel-tooth bits have steel teeth formed integral to the cone. (A hardmetal is typically applied to the surface of the teeth to improve the wear resistance of the structure.) Insert bits have very hard inserts (e.g. specially selected grades of tungsten carbide) pressed into holes drilled into the cone surfaces. The inserts extend outwardly beyond the surface of the cones to form the "teeth" that comprise the cutting structures of the drill bit.

The design of the component elements in a rock bit are interrelated (together with the size limitations imposed by the overall diameter of the bit), and some of the design parameters are driven by the intended use of the product. For example, cone angle and offset can be modified to increase or decrease the amount of bottom hole scraping. Many other design parameters are limited in that an increase in one parameter may necessarily result in a decrease of another. For example, increases in tooth length may cause interference with the adjacent cones.

Background: Tooth Design

The teeth of steel tooth bits are predominantly of the inverted "V" shape. The included angle (i.e. the sharpness of the tip) and the length of the tooth will vary with the design of the bit. In bits designed for harder formations the teeth will be shorter and the included angle will be greater. Gage row teeth (i.e. the teeth in the outermost row of the cone, next to the outer diameter of the borehole) may have a "T" shaped crest for additional wear resistance.

The most common shapes of inserts are spherical, conical, and chisel. Spherical inserts have a very small protrusion and are used for drilling the hardest formations. Conical inserts have a greater protrusion and a natural resistance to breakage, and are often used for drilling medium hard formations.

Chisel shaped inserts have opposing flats and a broad elongated crest, resembling the teeth of a steel tooth bit. Chisel shaped inserts are used for drilling soft to medium formations. The elongated crest of the chisel insert is normally oriented in alignment with the axis of cone rotation. Thus, unlike spherical and conical inserts, the chisel insert may be directionally oriented about its center axis. (This is true of any tooth which is not axially symmetric.) The axial angle of orientation is measured from the plane intersecting the center of the cone and the center of the tooth.

Background: Rock Mechanics and Formations

There are many factors that determine the drillability of a formation. These include, for example, compressive strength, hardness and/or abrasivity, elasticity, mineral content (stickiness), permeability, porosity, fluid content and interstitial pressure, and state of underground stress.

Soft formations were originally drilled with "fish-tail" drag bits, which sheared the formation away. Roller cone bits designed for drilling soft formations are designed to maximize the gouging and scraping action. To accomplish this, cones are offset to induce the largest allowable deviation from rolling on their true centers. Journal angles are small and cone-profile angles will have relatively large variations. Teeth are long, sharp, and widely-spaced to allow for the greatest possible penetration. Drilling in soft formations is characterized by low weight and high rotary speeds.

Hard formations are drilled by applying high weights on the drill bits and crushing the formation in compressive failure. The rock will fail when the applied load exceeds the strength of the rock. Roller cone bits designed for drilling hard formations are designed to roll as close as possible to a true roll, with little gouging or scraping action. Offset will be zero and journal angles will be higher. Teeth are short and closely spaced to prevent breakage under the high loads. Drilling in hard formations is characterized by high weight and low rotary speeds.

Medium formations are drilled by combining the features of soft and hard formation bits. The rock breaks away (is failed) by combining compressive forces with limited shearing and gouging action that is achieved by designing drill bits with a moderate amount of offset. Tooth length is designed for medium extensions as well. Drilling in medium formations is most often done with weights and rotary speeds between that of the hard and soft formations. Area drilling practices are evaluated to determine the optimum combinations.

Background: Roller Cone Bit Interaction with the Formation

In addition to improving drilling efficiency, the study of bottom hole patterns has allowed engineers to prevent detrimental phenomena such as those known as tracking, and gyration. The impressions a tooth makes into the formation depend largely on the design of the tooth, the tangential and radial scraping motions of the tooth, the force and speed with which the tooth impacts the formation, and the characteristics of the formation. Tracking occurs when the teeth of a drill bit fall into the impressions in the formation formed by other teeth at a preceding moment in time during the revolution of the drill bit. Gyration occurs when a drill bit fails to drill on-center. Both phenomena result in slow rates of penetration, detrimental wear of the cutting structures and premature failure of bits. Other detrimental conditions include excessive uncut rings in the bottom hole pattern. This condition can cause gyration, result in slow rates of penetration, detrimental wear of the cutting structures and premature failure of the bits. Another detrimental phenomenon is bit lateral vibration, which can be caused by radial force imbalances, bit mass imbalance, and bit/formation interaction among other things. This condition includes directional reversals and gyration about the hole center often known as whirl. Lateral vibration results in poor bit performance, overgage hole drilling, out-of-round, or "lobed" wellbores, and premature failure of both the cutting structures and bearing systems of bits. (Kenner and Isbell, DYNAMIC ANALYSIS REVEALS STABILITY OF ROLLER CONE ROCK BITS, SPE 28314, 1994).

Background: Bit Design

Currently, roller cone bit designs remain the result of generations of modifications made to original designs. The modifications are based on years of experience in evaluating bit records, dull bit conditions, and bottom hole patterns.

One method commonly used to discourage bit tracking is known as a staggered tooth design. In this design the teeth are located at unequal intervals along the circumference of the cone. This is intended to interrupt the recurrent pattern of impressions on the bottom of the hole. Examples of this are shown in U.S. Pat. No. 4,187,922 and UK application 2,241,266.

Background: Shortcomings of Existing Bit Designs

The economics of drilling a well are strongly reliant on rate of penetration. Since the design of the cutting structure of a drill bit controls the bit's ability to achieve a high rate of penetration, cutting structure design plays a significant role in the overall economics of drilling a well. Current bit designs have not solved the issue of tracking. Complex mathematical models can simulate bottom hole patterns to a limited extent, but they do not suggest a solution to the ever-present problem of tracking. The known angular orientations of teeth designed to improve tooth impact strength leave excessive uncut bottom hole patterns and do not solve the problem of tracking. The known angular orientations of teeth designed to increase bottom hole coverage, fail to optimize tooth orientation and do not solve the problem of tracking. Staggered tooth designs do not prevent tracking of the outermost rows of teeth. On the outermost rows of each cone, the teeth are encountering impressions in the formation left by teeth on other cones. The staggered teeth are just as likely to track an impression as any other tooth. Another disadvantage to staggered designs is that they may cause fluctuations in cone rotational speed, resulting in fluctuations in tooth impact force and increased bit vibration. Bit vibration is very harmful to the life of the bit and the life of the entire drill string.

Background: Cutting Structure Design

In the publication A NEW WAY TO CHARACTERIZE THE GOUGING-SCRAPING ACTION OF ROLLER CONE BITS (Ma, Society of Petroleum Engineers No. 19448, 1989), the author determines that a tooth in the first (heel or gage) row of the drill bit evaluated contacts the formation at −22 degrees (measured with respect to rotation of the cone about its journal) and begins to separate at an angle of −6 degrees. The author determines that the contacting range for the second row of the same cone is from

–26 degrees to 6 degrees. The author states that "because the crest of the chisel inserts are always in the parallel direction with the generatrix of the roller cone . . . radial scraping will affect the sweep area only slightly." The author concludes that scraping distance is a more important than the velocity of the cutter in determining performance.

In U.S. Pat. No. 5,197,555, Estes discloses a roller cone bit having opposite angular axial orientation of chisel shaped inserts in the first and second rows of a cone. This invention is premised on the determination that inserts scrape diagonally inboard and either to the leading side (facing in the direction of rotation) or to the trailing side (facing opposite to the direction of rotation). It is noted that the heel row inserts engage the formation to the leading side, while the second row inserts engage the formation to the trailing edge. In one embodiment, the inserts in the heel row are axially oriented at an angle between 30 degrees and 60 degrees, while the inserts in the second row are axially oriented between 300 degrees and 330 degrees. This orientation is designed to provide the inserts with a higher resistance to breakage. In an alternative embodiment, the inserts in the heel row are oriented at an axial angle between 300 degrees and 330 degrees, while the inserts in the second row are axially oriented between 30 degrees and 60 degrees. This orientation is designed to provide the inserts with a broader contact area with the formation for increased formation removal, and thereby an increased rate of penetration of the drill bit into the formation.

Summary: Roller-Cone Bits, Systems, Drilling Methods, and Design Methods with Optimization of Tooth Orientation

The present application describes bit design methods (and corresponding bits, drilling methods, and systems) in which tooth orientation is optimized jointly with other parameters, using software which graphically displays the linearized trajectory of each tooth row, as translated onto the surface of the cone. Preferably the speed ratio of each cone is precisely calculated, as is the curved trajectory of each tooth through the formation. However, for quick feedback to a design engineer, linear approximations to the tooth trajectory are preferably displayed.

The disclosed innovations, in various embodiments, provide one or more of at least the following advantages:

- The disclosed methods provide a very convenient way for designers to take full advantage of the precision of a computer-implemented calculation of geometries. (The motion over hole bottom of roller cone bit teeth is so complex that only a complex mathematical model and associated computer program can provide accurate design support.)
- The disclosed methods provide convenient calculation of tooth trajectory over the hole bottom during the period when the tooth engages into and disengages from the formation.
- The disclosed methods permit the orientation angle of teeth in all rows to be accurately determined based on the tooth trajectory.
- The disclosed methods permit the influence of tooth orientation changes on bit coverage ratio over the hole bottom to be accurately estimated and compensated.
- The disclosed methods also permit designers to optimally select different types of teeth for different rows, based on the tooth trajectory.

The following patent application describes roller cone drill bit design methods and optimizations which can be used separately from or in synergistic combination with the methods disclosed in the present application. That application, which has common ownership, inventorship, and effective filing date with the present application, is: application Ser. No. 09/387,737, filed Aug. 31, 1999, entitled "Force-Balanced Roller-Cone Bits, Systems, Drilling Methods, and Design Methods" (atty. docket no. SC-9825), claiming priority from U.S. provisional application No. 60/098,466 filed Aug. 31, 1998.

That nonprovisional application, and its provisional priority application, are both hereby incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWING

The disclosed inventions will be described with reference to the accompanying drawings, which show important sample embodiments of the invention and which are incorporated in the specification hereof by reference, wherein:

FIGS. 1A–1C shows a sample embodiment of a bit design process, using the teachings of the present application.

FIG. 2 shows the tangential and radial velocity components of tooth trajectory, viewed through the cutting face (i.e. looking up).

FIGS. 3A, 3B, 3C, and 3D show plots of planar tooth trajectories for teeth in four rows of a single cone, referenced to the XY coordinates of FIG. 2.

FIGS. 4A and 4B show tangential and radial distances, respectively, for the four tooth trajectories shown in FIGS. 3A–3D.

FIG. 5 is a sectional view of a cone (normal to its axis), showing how the tooth orientation is defined.

FIG. 6 shows time-domain plots of tooth tangential speed, for the five rows of a sample cone, over the duration of the trajectory for each row.

FIGS. 7A and 7B show how optimization of tooth orientation can perturb the width of uncut rings on the hole bottom.

FIGS. 8A and 8B show how optimization of tooth orientation can disturb the tooth clearances.

FIGS. 9A, 9B and 9C show the screen views which a skilled bit designer would see, according to some embodiments of the invention, while working on a bit optimization which included optimization of tooth orientation.

FIG. 10 shows a drill rig in which bits optimized by the teachings of the present application can be advantageously employed.

FIG. 11 shows a conventional roller cone bit, and FIG. 12 shows a conventional drag bit.

FIG. 13 shows a sample XYZ plot of a non-axisymmetric tooth tip.

FIG. 14 shows axial and sectional views of the i-th cone, and illustrates the enumeration of rows and teeth.

FIGS. 15A–15D show how the planarized tooth trajectories vary as the offset is increased.

FIGS. 16A–16D show how the ERSD and ETSD values vary for all rows of a given cone as offset is increased.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The numerous innovative teachings of the present application will be described with particular reference to the presently preferred embodiment (by way of example, and not of limitation).

Overview of Sample Design Process

FIGS. 1A–1C show a sample embodiment of a bit design process, using the teachings of the present application.

Specifically, FIG. 1A shows an overview of the design process, and FIGS. 1B and 1C expand specific parts of the process.

First, the bit geometry, rock properties, and bit operational parameters are input (step 102). Then the 3D tooth shape, cone profile, cone layout, 3D cone, 3D bit, and 2D hole profile are displayed (step 104).

Since there are two types of rotation relevant to the calculation of the hole bottom (cone rotation and bit rotation), transformation matrices from cone to bit coordinates must be calculated (step 106). (See FIG. 1B.) The number of bit revolutions is input (step 108), and each cone is counted (step 110), followed by each row of teeth for each cone (step 112). Next, the type of teeth of each row is identified (step 114), and the teeth are counted (step 116). Next, a time interval delta is set (step 118), and the position of each tooth is calculated at this time interval (step 120). If a given tooth is not "cutting" (i.e., in contact with the hole bottom), then the algorithm continues counting until a cutting tooth is reached (step 122). The tooth trajectory, speed, scraping distance, crater distribution, coverage ratio and tracking ratios for all rows, cones, and the bit are calculated (step 124). This section of the process (depicted in FIG. 1B) gives the teeth motion over the hole bottom, and displays the results (step 126).

Next the bit mechanics are calculated. (See FIG. 1C.) Again transformation matrices from cone to bit coordinates are calculated (step 128), and the number of bit revolutions and maximum time steps, delta, are input (step 130). The cones are then counted (step 132), the bit and cone rotation angles are calculated at the given time step (step 134), and the rows are counted (step 136). Next, the 3D tooth surface matrices for the teeth on a given row are calculated (step 138). The teeth are then counted (step 140), and the 3D position of the tooth on the hole bottom is calculated at the given time interval (step 142). If a tooth is not cutting, counting continues until a cutting tooth is reached (step 144). The cutting depth, area, volume and forces for each tooth are calculated, and the hole bottom model is updated (based on the crater model for the type of rock being drilled). Next the number of teeth cutting at any given time step is counted. The tooth force is projected into cone and bit coordinates, yielding the total cone and bit forces and moments. Finally the specific energy of the bit is calculated (step 146).

Finally, all results are outputted (step 148). The process can then be reiterated if needed.

Four Coordinate Systems

Four coordinate systems are used, in the presently preferred embodiment, to define the crest point of a tooth in three dimensional space. All the coordinate system obey the "Right Hand Rule". These coordinate systems—tooth, cone, bit, and hole—are described below.

Local Tooth Coordinates

FIG. 13 shows a sample XYZ plot of a tooth tip (in tooth local coordinates). Tooth coordinates will be indicated here by the subscript t. (Of course, each tooth has its own tooth coordinate system.) The center of the $X_tY_tZ_t$ coordinate system, in the presently preferred embodiment, is located at the tooth center. The coordinate of a tooth's crest point P_t will be defined by parameters of the tooth profile (e.g. tooth diameter, extension, etc.).

Cone Coordinates

FIG. 14 shows axial and sectional views of the i-th cone, and illustrates the enumeration of rows and teeth. Cone coordinates will be indicated here by the subscript c. The center of the cone coordinates is located in the center of backface of the cone. The cone body is fixed with respect to these coordinates, and hence THESE COORDINATES ROTATE WITH THE CONE. (Of course, each cone has its own cone coordinate system.) The axis Z_c coincides with the cone axis, and is oriented towards to the bit center. Cone axes Y_c and X_c, together with axis Z_c, follow the right hand rule. As shown in FIG. 13, four parameters are enough to completely define the coordinate of the crest point of a tooth on cone profile. These four parameters are H_c, R_c, ϕ_c and θ_c. For all the teeth on the same row, H_c, R_c, and ϕ_c are the same.

Bit Coordinates

Similarly, a set of bit axes $X_bY_bZ_b$, indicated by the subscript b, is aligned to the bit. The bit is fixed with respect to these coordinates, and hence THESE COORDINATES ROTATE WITH THE BIT. Axis Z_b preferably points toward the cutting face, and axes X_b and Y_b are normal to Z_b (and follow the right-hand rule).

Hole Coordinates

The simplest coordinate system is defined by the hole axes $X_hY_hZ_h$, which are fixed in space. Note however that axes Z_b and Z_h may not be coincident if the bit is tilted. FIG. 2 shows the tangential and radial velocity components of tooth trajectory, viewed through the cutting face (i.e. looking up). Illustrated is a small portion of a tooth trajectory, wherein a tooth's crest (projected into an X_hY_h plane which approximates the bottom of the hole) moves from point A to point B, over an arc distance ds and a radial distance dr.

Transformations

Since all of these coordinate systems are xyz systems, they can be interrelated by simple matrix transformations.

Both the bit and the cones are rotating with time. In order to calculate the position on hole bottom where the crest point of a tooth engages into formation, and the position that the crest point of a tooth disengages from formation, all the teeth positions at any time must be described in hole coordinate system XhYhZh.

The transformation from tooth coordinates $X_tY_tZ_t$ to cone coordinates $X_cY_cZ_c$ can be defined by a matrix Rtc, which is a matrix function of teeth parameters:

$$Rtc=f(H_c, R_c, \theta_c, \phi_c),$$

so that any point P_t in $X_tY_tZ_t$ can be transformed into local cone coordinates $X_cY_cZ_c$ by:

$$P_c=R_{tc}*P_t$$

At time t=0, it is assumed that the plane $X_cO_cZ_c$ is parallel to the bit axis. At time t, the cone has a rotation angle λ around its negative axis ($-Z_c$). Any point on the cone moves to a new position due to this rotation. The new position of P_c in $X_cY_cZ_c$ can be determined by combining linear transforms.

The transform matrix due to cone rotation is R_{cone}:

$$R_{cone}=\cos(\lambda)I+(1-\cos(\lambda))NcNc'+\sin(\lambda)Mc.$$

where N_c is the rotation vector and M_c is a 3*3 matrix defined by N_c.

Therefore, the new position P_{crot} of P_c due to cone rotation is:

$$P_{crot}=R_{cone}*P_c$$

Let R_{cb1}, R_{cb2}, and R_{cb3} be respective transformation matrices (for cones 1, 2, and 3) from cone coordinate to bit coordinates. (These matrices will be functions of bit parameters such as pin angle, offset, and back face length.) Any point P_{ci} in cone coordinates can then be transformed into bit coordinates by:

$$P_{bi}=R_{cbi}*P_{ci}+P_{c0i} \text{ for } i=1, 2, \text{ or } 3.$$

where P_{c0i} is the origin of cone coordinates in the bit coordinate system.

The bit is rotating around its own axis. Let us assume that the bit axes and hole axes are coincident at time t=0. At time t, the bit has a rotation angle β. The transform matrix due to bit rotation is:

$$Rbh=\cos(\beta)I+(1-\cos(\beta))NbNb'+\sin(\beta)Mb$$

where Nb is the rotation vector and Mb is a 3*3 matrix defined by Nb. Therefore, any point Pb in bit coordinate system can be transformed into the hole coordinate system X_h,Y_h,Z_h by:

$$Ph=Rbh*Pb.$$

Therefore, the position of the crest point of any tooth at any time in three dimensional space has been fully defined by the foregoing seven equations. In order to further determine the engage and disengage point the formation is modeled, in the presently preferred embodiment, by multiple stepped horizontal planes. (The number of horizontal planes depends on the total number of rows in the bit.) In this way, the trajectory of any tooth on hole bottom can be determined.

Calculation of Trajectories in Bottomhole Plane

With the foregoing transformations, the trajectory of the tooth crest across the bottom of the hole can be calculated. FIGS. 3A, 3B, 3C, and 3D show plots of planar tooth trajectories, referenced to the hole coordinates X_h,Y_h, for teeth on four different rows of a particular roller cone bit. The teeth on the outermost row (first row) scrapes toward the leading side of the cone. Its radial and tangential scraping distances are similar, as can be seen by comparing the first bar in FIG. 4A with the first bar in FIG. 4B. However for teeth on the second row the radial scraping motion is much larger than the tangent motion. The teeth on the third row scrape toward the trailing side of the cone, and the teeth on the forth row scrape toward the leading side of the cone.

FIGS. 4A and 4B show per-bit-revolution tangential and radial distances, respectively, for the four tooth trajectories shown in FIGS. 3A–3D. Note that, in this example, the motion of the second row is almost entirely radial, and not tangential.

Projection of Trajectories into Cone Coordinates

The tooth trajectories described above are projected on the hole bottom which is fixed in space. In this way it is clearly seen how the tooth scrapes over the bottom. However for the bit manufacturer or bit designer it is necessary to know the teeth orientation angle on the cone coordinate, in order either to keep the elongate side of the tooth perpendicular to the scraping direction (for maximum cutting rate in softer formations) or to keep the elongate side of the tooth in line with the scraping direction (for durability in harder formations). To this end the tooth trajectories are projected to the cone coordinate system. Let $P_1=\{x_1, y_1, z_1\}_c$ and $P_2=\{x_2, y_2, z_2\}_c$ be the engage and disengage points on cone coordinate system, respectively, and approximate the tooth trajectory P_1–P_2 as a straight line. Then the scraping angle in cone coordinates is:

$$R_s=\sqrt{(x_2-x_1)^2+(y_1+y_2)^2}$$

and

$$\gamma_s=\tan^{-1}\left(\frac{R_s}{z_2-z_1}\right)$$

The teeth can then be oriented appropriately with respect to this angle gamma. For example, for soft formation drilling the tooth would preferably be oriented so that its broad side is perpendicular to the scraping direction, in order to increase its rate of rock removal. In this case, the direction γ_c of the elongate crest of the tooth, in cone coordinates, is normal to γ_s, i.e. $\gamma_c=\gamma_s+\pi/2$. Conversely, for drilling harder formations with a chisel-shaped tooth it might be preferable to orient the tooth with minimum frontal area in the direction of scraping, i.e. with $\gamma_c=\gamma_s$.

Derivation of Equivalent Radial and Tangential Scraping

There are numerous parameters in roller cone design, and experienced designers already know, qualitatively, that changes in cone shape (cone angle, heel angle, third angle, and oversize angle) as well as offset and journal angle will affect the scraping pattern of teeth in order to get a desired action-on-bottom. One problem is that it is not easy to describe a desired action-on-bottom quantitatively. The present application provides techniques for addressing this need.

Two new parameters have been defined in order to quantitatively evaluate the cone shape and offset effects on tooth scraping motion. Both of these parameters can be applied either to a bit or to individual cones.

(1) Equivalent Tangent Scraping Distance (ETSD) is equal to the total tangent scraping distance of all teeth on a cone (or bit) divided by the total number of the teeth on the cone (or bit).

(2) Equivalent Radial Scraping Distance (ERSD) is equal to the total radial scraping distance of all teeth on a cone (or bit) divided by the total number of the teeth on the cone (or bit).

Both of these two parameters they have much more clear physical meaning than the offset value and cone shape.

Surprisingly, the arcuate (or bulged) shape of the cone primarily affects the ETSD value, and the offset determines the ERSD value. Also surprisingly, the ERSD is not equal to zero even at zero offset. In other words, the teeth on a bit without offset may still have some small radial scraping effects.

The radial scraping direction for all teeth is always toward to the hole center (positive). However, the tangential scraping direction is usually different from row to row.

In order to use the scraping effects fully and effectively, the leading side of the elongated teeth crest should be orientated at an angle to the plane of the cone's axis, which is calculated as described above for any given row.

FIG. 2 shows the procedure in which a tooth cuts into (point A) and out (point B) the formation. Due to bit offset, arcuate cone shape and bit and cone rotations, the motion from A to B can be divided into two parts: tangent motion ds and radial motion dr. Notice the tangent and radial motions are defined in hole coordinate system XhYh. Because ds and dr vary from row to row and from cone to cone, we derive an equivalent tangent scraping distance (ETSD) and an equivalent radial scraping distance (ERSD) for a whole cone (or for an entire bit).

For a cone, we have

$$ETSD = \frac{\sum_{j}^{Nr} ds_j Nt_j}{Nc}$$

and

$$ERSD = \frac{\sum_{j}^{Nr} dr_j Nt_j}{Nc}$$

where Nc is the total tooth count of a cone and Nr is the number of rows of a cone.

Similarly for a bit, we have

$$ETSD = \frac{\sum_{i}^{3}\sum_{j}^{Nr} ds_{ij} Nt_{ij}}{Nb}$$

and

$$ERSD = \frac{\sum_{i}^{3}\sum_{j}^{Nr} dr_{ij} Nt_{ij}}{Nb}$$

where Nb is the total tooth count of the bit.

FIGS. 15A–15D show how the planarized tooth trajectories vary as the offset is increased. These figures clearly show that with the increase of the offset value, the radial scraping distance is increased. Surprisingly, the radial scraping distance is not equal to zero even if the offset is zero. This is due to the arcuate shape of the cone.

FIGS. 16A–16D show how the ERSD and ETSD values vary for all rows of a given cone as offset is increased. From these Figures, it can be seen that the tangent scraping distance of the gage row, while very small compared to other rows but is not equal to zero. It means that there is a sliding even for the teeth on the driving row. This fact may be explained by looking at the tangent speed during the entry and exit of teeth into and out of the rock. (FIG. 6 shows time-domain plots of tooth tangential speed, for the five rows of a sample cone, over the duration of the trajectory for each row.) During the cutting procedure the tangent speed is not equal to zero except for one instant. Because the sliding speed changes with time, the instantaneous speed is not the best way to describe the teeth/rock interaction.

Note that the tangent scraping directions are different from row to row for the same cone. FIG. 5 is a sectional view of a cone (normal to its axis), showing how the tooth orientation is defined in the present application: the positive direction is defined as the same direction as the bit rotation. This means that the leading side of tooth on one row may be different from that on another row.

The ERSD increases almost proportionally with the increase of the bit offset. However, ERSD is not zero even if the bit offset is zero. This is because the radial sliding speed is not always zero during the procedure of tooth cutting into and cutting out the rock.

Calculation of Uncut Rings, and Row Position Adjustment

FIGS. 7A and 7B show how optimization of tooth orientation can perturb the width of uncut rings on the hole bottom. The width of uncut rings is one of the design constraints: a sufficiently narrow uncut ring will be easily fractured by adjacent cutter action and mud flows, but too large an uncut ring will slow rate of penetration. Thus one

of the significant teachings of the present application is that tooth orientation should not be adjusted in isolation, but preferably should be optimized jointly with the width of uncut rings.

Interference Check

Another constraint is tooth interference. In the crowded geometries of an optimized roller cone design, it is easy for an adjustment to row position to cause interference between cones. FIGS. 8A and 8B graphically show how optimization of tooth orientation can disturb the tooth clearances. Thus optimization of tooth orientation is preferably followed by an interference check (especially if row positions are changed).

Iteration

Preferably multiple iterations of the various optimizations are used, to ensure that the various constraints and/or requirements are all jointly satisfied according to an optimal tradeoff.

Graphic Display

The scraping motion of any tooth on any row is visualized on the designer's computer screen. The bit designer has a chance to see quantitatively how large the motion is and in which direction if bit geometric parameters like cone shape and offset are changed.

FIGS. 9A, 9B and 9C show the screen views which a skilled bit designer would see, according to some embodiments of the invention, while working on a bit optimization which included optimization of tooth orientation. These three views show representations of tooth orientation and scraping direction for each tooth row on each of the three cones. This simple display allows the designer to get a feel for the effect of various parameter variations

Calculation of Cone/Bit Rotation Ratio

The present application also teaches that the ratio between the rotational speeds of cone and bit can be easily checked, in the context of the detailed force calculations described above, simply by calculating the torques about the cone axis. If these torques sum to zero (at a given ratio of cone and bit speed), then the given ratio is correct. If not, an iterative calculation can be performed to find the value of this ratio.

However, it should be noted that the exact calculation of the torque on the cones is dependent on use of a solid-body tooth model, as described above, rather than a mere point approximation.

Previous simulations of roller cone bits have assumed that the gage row is the "driving" row, which has no tangential slippage against the cutting face. However, this is a simplification which is not completely accurate. Accurate calculation of the ratio of cone speed to bit speed shows that it is almost never correct, if multiple rows of teeth are present, to assume that the gage row is the driver.

Changes in the tooth orientation angle will not themselves have a large immediate effect on the cone speed ratio. However, the tooth orientation affects the width of uncut rings, and excessive uncut ring width can require the spacing of tooth rows to be changed. Any changes in the spacing of tooth rows will probably affect the cone speed ratio.

Definitions:

Following are short definitions of the usual meanings of some of the technical terms which are used in the present application. (However, those of ordinary skill will recognize whether the context requires a different meaning.) Additional definitions can be found in the standard technical dictionaries and journals.

Drag bit: a drill bit with no moving parts that drills by intrusion and drag.

Mud: the liquid circulated through the wellbore during rotary drilling operations, also referred to as drilling fluid.

Originally a suspension of earth solids (especially clays) in water, modern "mud" is a three-phase mixture of liquids, reactive solids, and inert solids.

Nozzle: in a passageway through which the drilling fluid exits a drill bit, the portion of that passageway which restricts the cross-section to control the flow of fluid.

Orientation: the angle of rotation with which a non-axisymmetric tooth is inserted into a cone. Note that a tooth which is axisymmetric (e.g. one having a hemi-spherical tip) cannot have an orientation.

Roller cone bit: a drilling bit made of two, three, or four cones, or cutters, that are mounted on extremely rugged bearings. Also called rock bits. The surface of each cone is made up of rows of steel teeth (generally for softer formations) or rows of hard inserts (typically of tungsten carbide) for harder formations.

According to a disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit, comprising the steps of: adjusting the orientation of at least one tooth on a cone, in dependence on an expected trajectory of said tooth through formation material at the cutting face, in dependence on an estimated ratio of cone rotation to bit rotation; recalculating said ratio, if the location of any row of teeth on said cone changes during optimization; recalculating the trajectory of said tooth in accordance with a recalculated value of said cone speed; and adjusting the orientation of said tooth again, in accordance with a recalculated value of said tooth trajectory.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit, comprising the steps of: calculating the trajectory of at least one tooth on each cone through formation material at the cutting face; and jointly optimizing both the orientations of said teeth and the width of uncut rings on said cutting face, in dependence on said trajectory.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit comprising the steps of: a) adjusting the orientation of at least one row of teeth on a cone, in dependence on an expected trajectory of said tooth through formation material at the cutting face; b) calculating the width of uncut rings of formation material, in dependence on the orientation of said row of teeth, and adjusting the position of said row of teeth in dependence on said calculated width; and c) recalculating the rotational speed of said cone, if the position of said row is changed, and accordingly recalculating said trajectory of teeth in said row.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit, comprising the steps of: calculating the respective trajectories, of at least two non-axisymmetric teeth in different rows of a roller cone bit, through formation material at the cutting face; and graphically displaying, to a design engineer, both said trajectories and also respective orientation vectors of said teeth, as the engineer adjusts design parameters.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit, comprising the steps of: calculating the curved trajectory of a non-axisymmetric tooth through formation material at the cutting face, as the bit and cones rotate; calculating a straight line approximation to said curved trajectory; and orienting said tooth with respect to said approximation, and not with respect to said curved trajectory.

According to another disclosed class of innovative embodiments, there is provided: A roller cone drill bit designed by any of the methods described above, singly or in combination.

According to another disclosed class of innovative embodiments, there is provided: A rotary drilling system, comprising: a roller cone drill bit designed by any of the methods described above, singly or in combination, a drill string which is mechanically connected to said bit; and a rotary drive which rotates at least part of said drill string together with said bit.

According to another disclosed class of innovative embodiments, there is provided: A method for rotary drilling, comprising the actions of: applying weight-on-bit and rotary torque, through a drill string, to a drill bit designed in accordance with any of the methods described above, singly or in combination.

Modifications and Variations

As will be recognized by those skilled in the art, the innovative concepts described in the present application can be modified and varied over a tremendous range of applications, and accordingly the scope of patented subject matter is not limited by any of the specific exemplary teachings given.

For example, the various teachings can optionally be adapted to two-cone or four-cone bits.

In the example of FIGS. 9A-9C the crest profiles of all rows except the gage rows are shown as identical (and their crest orientations are indicated by simple ellipses). However, this is not necessary: optionally the designer can be allowed to plug in different tooth profiles for different rows, and the optimization routines can easily substitute various tooth profiles as desired. In particular, various tooth shapes can be selected from a library of profiles, to fit the scraping motion of each row.

In one contemplated class of alternative embodiments, the orientations of teeth can be perturbed about the optimal value, to induce variation between the gage rows of different cones (or within an inner row of a single cone), to provide some additional resistance to tracking.

Of course the bit will also normally contain many other features besides those emphasized here, such as gage buttons, wear pads, lubrication reservoirs, etc. etc.

Additional general background, which helps to show the knowledge of those skilled in the art regarding implementations and the predictability of variations, may be found in the following publications, all of which are hereby incorporated by reference: APPLIED DRILLING ENGINEERING, Adam T. Bourgoyne Jr. et al., Society of Petroleum Engineers Textbook series (1991), OIL AND GAS FIELD DEVELOPMENT TECHNIQUES: DRILLING, J.-P. Nguyen (translation 1996, from French original 1993), MAKING HOLE (1983) and DRILLING MUD (1984), both part of the Rotary Drilling Series, edited by Charles Kirkley.

None of the description in the present application should be read as implying that any particular element, step, or function is an essential element which must be included in the claim scope: THE SCOPE OF PATENTED SUBJECT MATTER IS DEFINED ONLY BY THE ALLOWED CLAIMS. Moreover, none of these claims are intended to invoke paragraph six of 35 USC section 112 unless the exact words "means for" are followed by a participle.

What is claimed is:

1. A method of designing a roller cone bit, comprising the steps of:

adjusting the orientation of at least one tooth on a cone, in dependence on an expected trajectory of said tooth through formation material at the cutting face, in dependence on an estimated ratio of cone rotation to bit rotation;

recalculating said ratio, if the location of any row of teeth on said cone changes during optimization;

recalculating the trajectory of said tooth in accordance with a recalculated value of said cone speed; and

adjusting the orientation of said tooth again, in accordance with a recalculated value of said tooth trajectory.

2. The method of claim 1, wherein all said steps are reiterated.

3. The method of claim 1, wherein every tooth on said bit is non-axisymmetric.

4. A method of designing a roller cone bit, comprising the steps of:

calculating the trajectory of at least one tooth on each cone through formation material at the cutting face; and

jointly optimizing both the orientations of said teeth and the width of uncut rings on said cutting face, in dependence on said trajectory.

5. The method of claim 4, wherein every tooth on said bit is non-axisymmetric.

6. A method of designing a roller cone bit comprising the steps of:

a) adjusting the orientation of at least one row of teeth on a cone, in dependence on an expected trajectory of said tooth through formation material at the cutting face;

b) calculating the width of uncut rings of formation material, in dependence on the orientation of said row of teeth, and adjusting the position of said row of teeth in dependence on said calculated width; and

c) recalculating the rotational speed of said cone, if the position of said row is changed, and accordingly recalculating said trajectory of teeth in said row.

7. The method of claim 6, wherein said steps a), b), and c) are reiterated.

8. The method of claim 6, wherein every tooth on said bit is non-axisymmetric.

9. A method of designing a roller cone bit, comprising the steps of:

calculating the respective trajectories, of at least two non-axisymmetric teeth in different rows of a roller cone bit, through formation material at the cutting face; and

graphically displaying, to a design engineer, both said trajectories and also respective orientation vectors of said teeth, as the engineer adjusts design parameters.

10. The method of claim 9, wherein every tooth on said bit is non-axisymmetric.

11. A method of designing a roller cone bit, comprising the steps of:

calculating the curved trajectory of a non-axisymmetric tooth through formation material at the cutting face, as the bit and cones rotate;

calculating a straight line approximation to said curved trajectory; and

orienting said tooth with respect to said approximation, and not with respect to said curved trajectory.

12. The method of claim 11, wherein the step of calculating tooth trajectory in the formation as the bit rotates comprises the substeps of: defining coordinate systems for the teeth, cones, bit, and hole; and applying time-dependent matrix transformations to translate among said coordinate systems.

13. The method of claim 11, said step of calculating a straight-line representation of tooth trajectory comprises the actions of:

determining an entrance point representative of a tooth entering into the formation; determining an exit point representative of a tooth exiting from the formation; and calculating a straight line between the entrance point and exit point for each row of teeth.

14. The method of claim 11, wherein every tooth on said bit is non-axisymmetric.

15. A roller cone drill bit designed by the method of claim 1.

16. A roller cone drill bit designed by the method of claim 4.

17. A roller cone drill bit designed by the method of claim 6.

18. A roller cone drill bit designed by the method of claim 9.

19. A roller cone drill bit designed by the method of claim 11.

20. A rotary drilling system, comprising:

a roller cone drill bit designed by the method of claim 1;

a drill string which is mechanically connected to said bit from a surface location; and

a rotary drive which rotates at least part of said drill string together with said bit.

21. A method for rotary drilling, comprising the actions of: applying weight-on-bit and rotary torque, through a drill string, to a drill bit designed in accordance with claim 1.

* * * * *

US006213225B1

(12) **United States Patent**
Chen

(10) **Patent No.: US 6,213,225 B1**
(45) **Date of Patent: Apr. 10, 2001**

(54) **FORCE-BALANCED ROLLER-CONE BITS, SYSTEMS, DRILLING METHODS, AND DESIGN METHODS**

(75) Inventor: Shilin Chen, Dallas, TX (US)

(73) Assignee: Halliburton Energy Services, Inc., Carrollton, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: 09/387,737

(22) Filed: Aug. 31, 1999

Related U.S. Application Data

(60) Provisional application No. 60/098,466, filed on Aug. 31, 1998.

(51) Int. Cl.[7] E21B 10/16

(52) U.S. Cl. 175/57; 76/108.2; 175/331; 175/378

(58) Field of Search 175/331, 57, 353, 175/355, 356, 378; 76/108.2, 108.4

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,209,299 *	12/1916	Hughes	175/333
1,263,802 *	4/1918	Reed	175/340
1,394,769 *	10/1921	Sorensen	175/336
4,187,922	2/1980	Phelps	175/374
4,393,948	7/1983	Fernandez	175/374
4,627,276 *	12/1986	Burgess et al.	175/39
4,815,342 *	3/1989	Brett et al.	76/108 A
5,197,555	3/1993	Estes	175/431
5,216,917 *	6/1993	Detournay	175/39
5,305,836 *	4/1994	Holbrook et al.	175/39
5,704,436	1/1998	Smith et al.	175/27
5,767,399	6/1998	Smith et al.	73/152.11
5,794,720	8/1998	Smith et al.	175/40

FOREIGN PATENT DOCUMENTS

2241266 8/1991 (GB).

* cited by examiner

Primary Examiner—Hoang Dang
(74) *Attorney, Agent, or Firm*—Groover & Associates; Robert Groover; Betty Formby

(57) **ABSTRACT**

Roller cone drilling wherein the bit optimization process equalizes the downforce (axial force) for the cones (as nearly as possible, subject to other design constraints). Bit performance is significantly enhanced by equalizing downforce.

12 Claims, 8 Drawing Sheets

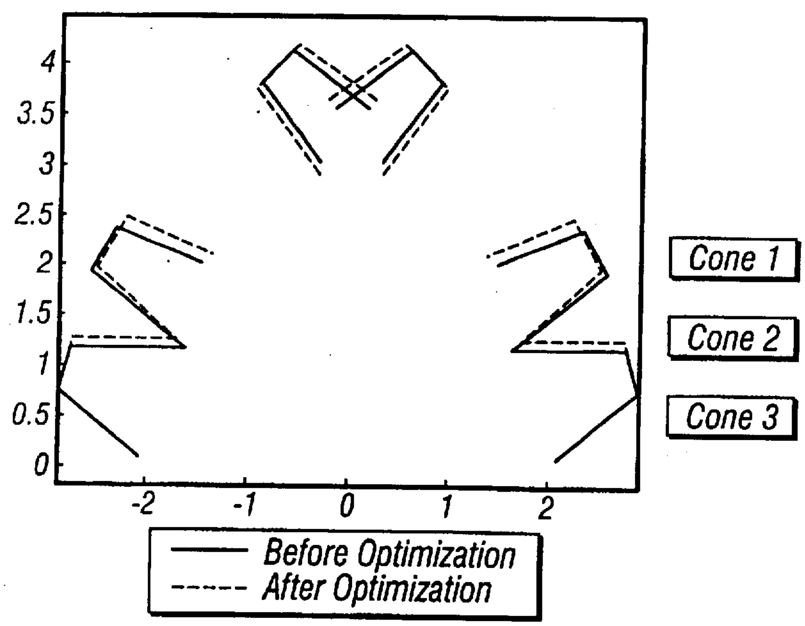


EXHIBIT A2

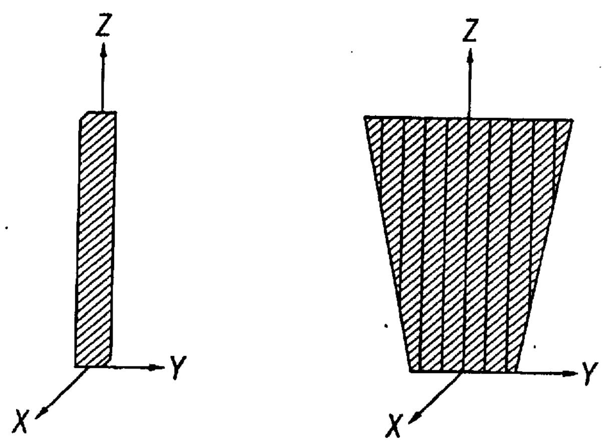

Z
Y
X
Z
Y
X

FIG. 1

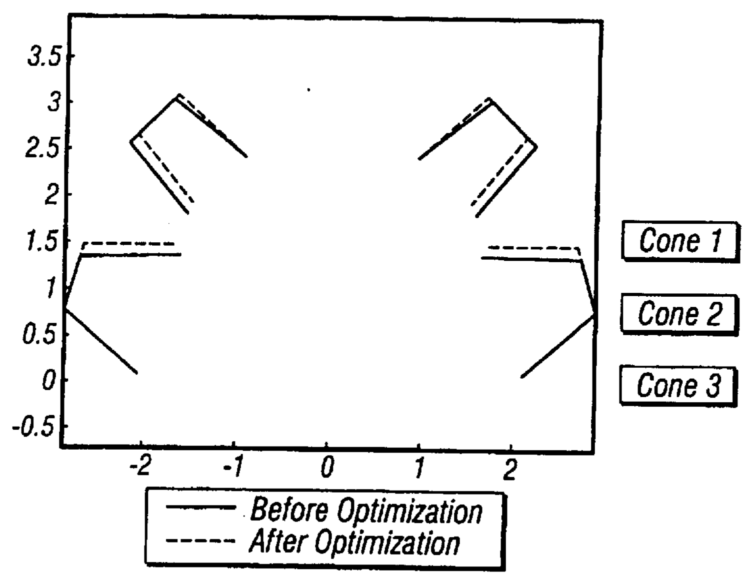

3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-2
-1
0
1
2
Cone 1
Cone 2
Cone 3
Before Optimization
After Optimization

FIG. 7C

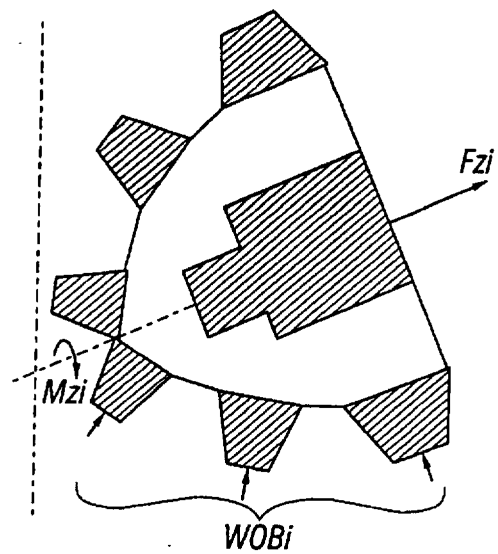


FIG. 2

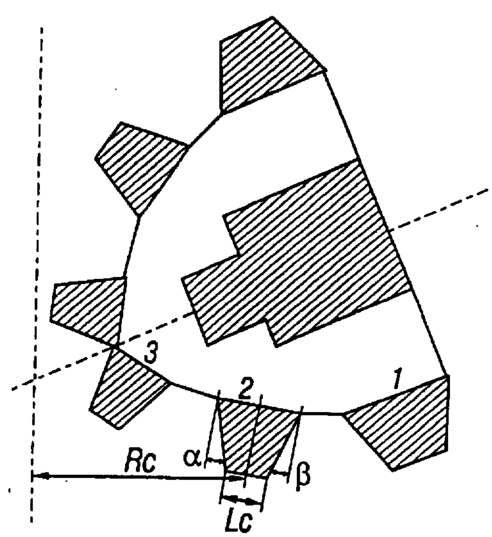


FIG. 3

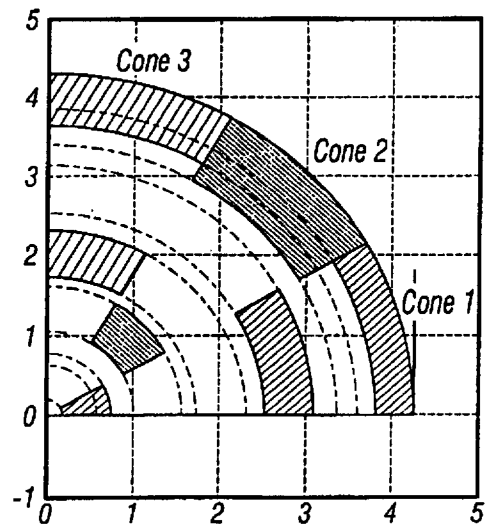


FIG. 4

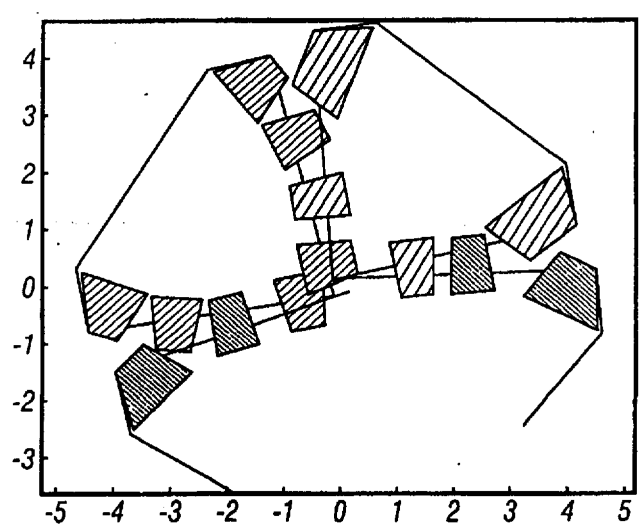


FIG. 5

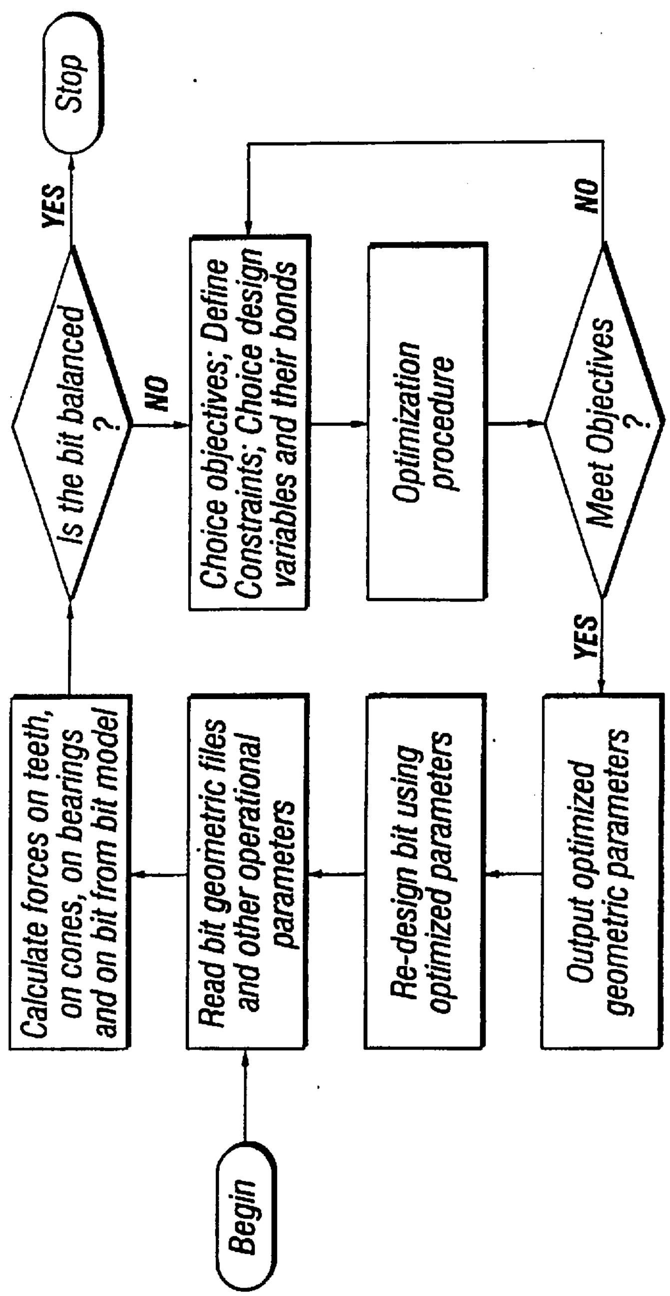

Begin
Read bit geometric files and other operational parameters
Calculate forces on teeth, on cones, on bearings and on bit from bit model
Is the bit balanced ?
YES
Stop
NO
Choice objectives; Define Constraints; Choice design variables and their bonds
Optimization procedure
Meet Objectives ?
NO
YES
Output optimized geometric parameters
Re-design bit using optimized parameters

FIG. 6

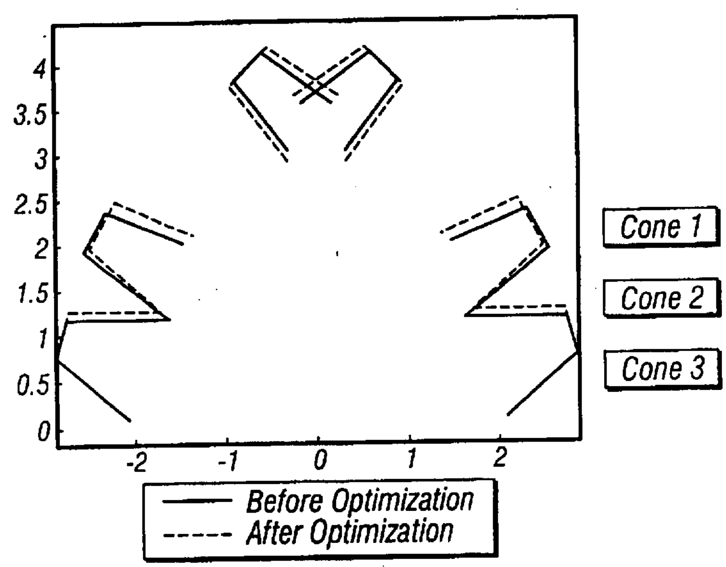
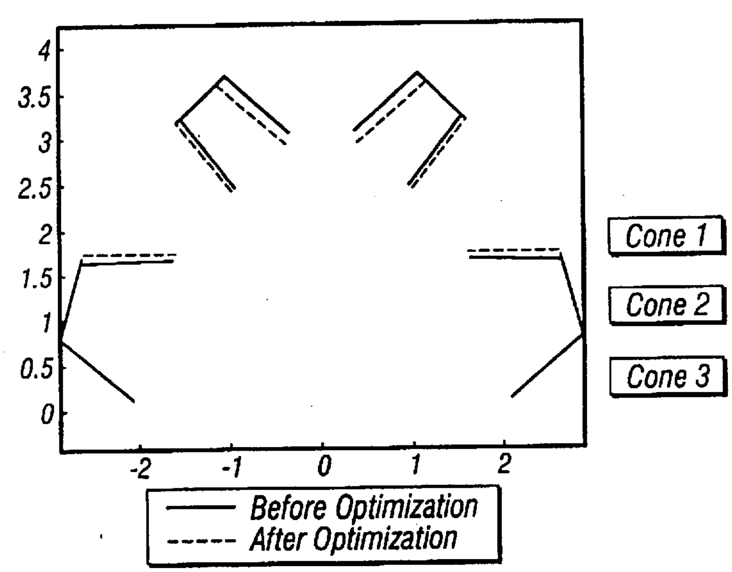

4
3.5
3
2.5
2
1.5
1
0.5
0
-2
-1
0
1
2
Cone 1
Cone 2
Cone 3
Before Optimization
After Optimization

FIG. 7A


4
3.5
3
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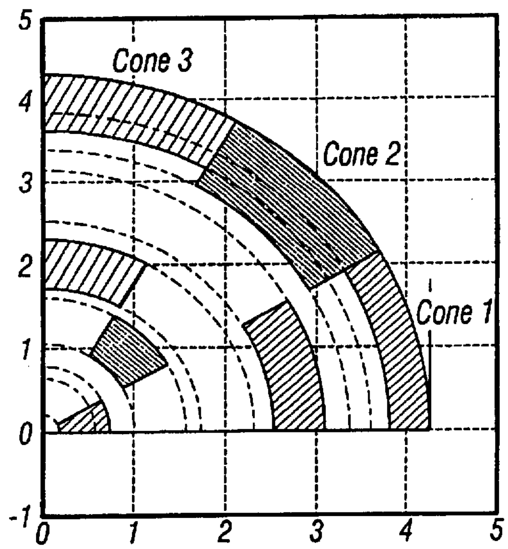
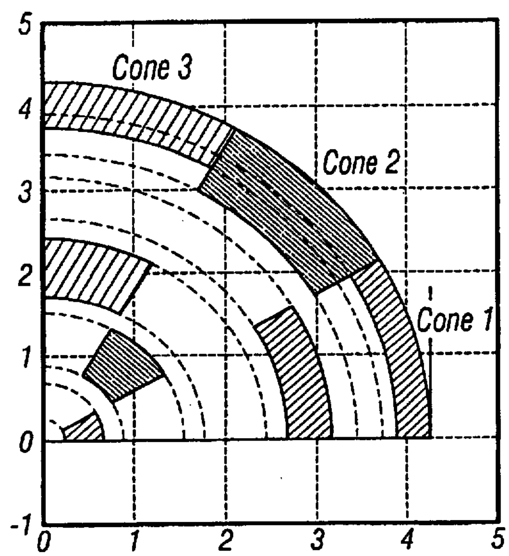
2
1.5
1
0.5
0
-2
-1
0
1
2
Cone 1
Cone 2
Cone 3
Before Optimization
After Optimization

FIG. 7B



Cone 3
Cone 2
Cone 1
5
4
3
2
1
0
-1
0
1
2
3
4
5

FIG. 8A



Cone 3
Cone 2
Cone 1
5
4
3
2
1
0
-1
0
1
2
3
4
5

FIG. 8B

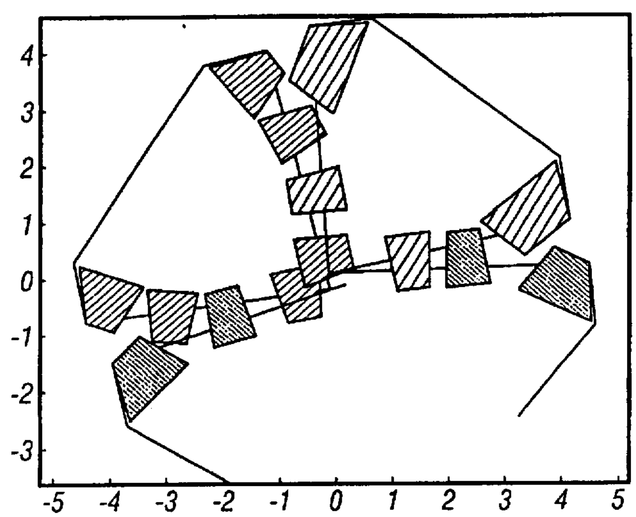


FIG. 9A

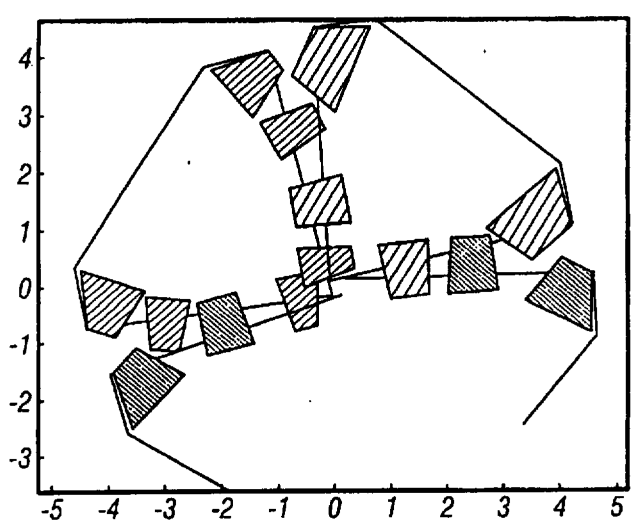


FIG. 9B

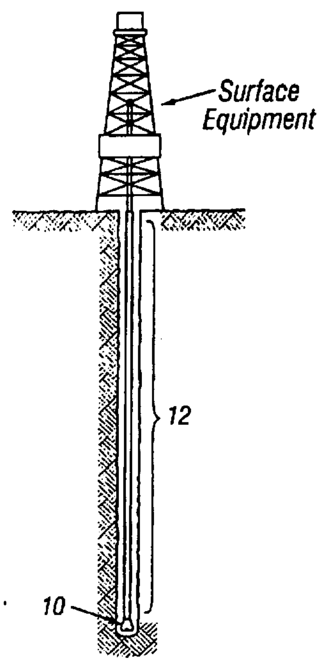


FIG. 10

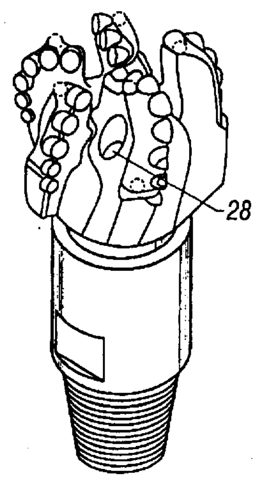


FIG. 11

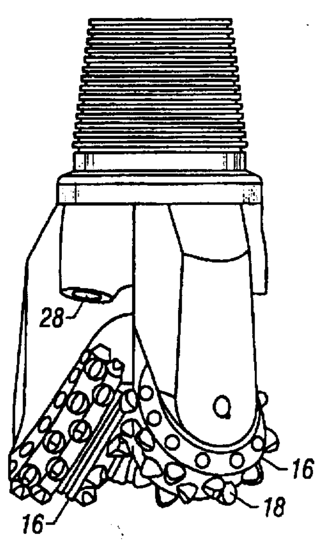


FIG. 12

FORCE-BALANCED ROLLER-CONE BITS, SYSTEMS, DRILLING METHODS, AND DESIGN METHODS

CROSS-REFERENCE TO OTHER APPLICATION

This application claims priority from U.S. provisional application No. 60/098,466 filed Aug. 31 1998, which is hereby incorporated by reference.

BACKGROUND AND SUMMARY OF THE INVENTION

The present invention relates to down-hole drilling, and especially to the optimization of drill bit parameters.

Background: Rotary Drilling

Oil wells and gas wells are drilled by a process of rotary drilling, using a drill rig such as is shown in FIG. 10. In conventional vertical drilling, a drill bit 10 is mounted on the end of a drill string 12 (drill pipe plus drill collars), which may be miles long, while at the surface a rotary drive (not shown) turns the drill string, including the bit at the bottom of the hole.

Two main types of drill bits are in use, one being the roller cone bit, an example of which is seen in FIG. 11. In this bit a set of cones 16 (two are visible) having teeth or cutting inserts 18 are arranged on rugged bearings on the arms of the bit. As the drill string is rotated, the cones will roll on the bottom of the hole, and the teeth or cutting inserts will crush the formation beneath them. (The broken fragments of rock are swept uphole by the flow of drilling fluid.) The second type of drill bit is a drag bit, having no moving parts, seen in FIG. 12.

There are various types of roller cone bits: insert-type bits, which are normally used for drilling harder formations, will have teeth of tungsten carbide or some other hard material mounted on their cones. As the drill string rotates, and the cones roll along the bottom of the hole, the individual hard teeth will induce compressive failure in the formation. The bit's teeth must crush or cut rock, with the necessary forces supplied by the "weight on bit" (WOB) which presses the bit down into the rock, and by the torque applied at the rotary drive.

Background: Drill String Oscillation

The individual elements of a drill string appear heavy and rigid. However, in the complete drill string (which can be more than a mile long), the individual elements are quite flexible enough to allow oscillation at frequencies near the rotary speed. In fact, many different modes of oscillation are possible. (A simple demonstration of modes of oscillation can be done by twirling a piece of rope or chain: the rope can be twirled in a flat slow circle, or, at faster speeds, so that it appears to cross itself one or more times.) The drill string is actually a much more complex system than a hanging rope, and can oscillate in many different ways; see WAVE PROPAGATION IN PETROLEUM ENGINEERING, Wilson C. Chin, (1994).

The oscillations are damped somewhat by the drilling mud, or by friction where the drill pipe rubs against the walls, or by the energy absorbed in fracturing the formation: but often these sources of damping are not enough to prevent oscillation. Since these oscillations occur down in the wellbore, they can be hard to detect, but they are generally undesirable. Drill string oscillations change the instantaneous force on the bit, and that means that the bit will not operate as designed. For example, the bit may drill oversize, or off-center, or may wear out much sooner than expected. Oscillations are hard to predict, since different mechanical forces can combine to produce "coupled modes"; the problems of gyration and whirl are an example of this.

Background: Optimal Drilling with Various Formation Types

There are many factors that determine the drillability of a formation. These include, for example, compressive strength, hardness and/or abrasiveness, elasticity, mineral content (stickiness), permeability, porosity, fluid content and interstitial pressure, and state of underground stress.

Soft formations were originally drilled with "fish-tail" drag bits, which sheared the formation. Fish-tail bits are obsolete, but shear failure is still very useful in drilling soft formations. Roller cone bits designed for drilling soft formations are designed to maximize the gouging and scraping action, in order to exploit both shear and compressive failure. To accomplish this, cones are offset to induce the largest allowable deviation from rolling on their true centers. Journal angles are small and cone-profile angles will have relatively large variations. Teeth are long, sharp, and widely-spaced to allow for the greatest possible penetration. Drilling in soft formations is characterized by low weight and high rotary speeds.

Hard formations are drilled by applying high weights on the drill bits and crushing the formation in compressive failure. The rock will fail when the applied load exceeds the strength of the rock. Roller cone bits designed for drilling hard formations are designed to roll as close as possible to a true roll, with little gouging or scrapping action. Offset will be zero and journal angles will be higher. Teeth are short and closely spaced to prevent breakage under the high loads. Drilling in hard formations is characterized by high weight and low rotary speeds.

Medium formations are drilled by combining the features of soft and hard formation bits. The rock is failed by combining compressive forces with limited shearing and gouging action that is achieved by designing drill bits with a moderate amount of offset. Tooth length is designed for medium extensions as well. Drilling in medium formations is most often done with weights and rotary speeds between that of the hard and soft formations.

Back Round: Roller Cone Bit Design

The "cones" in a roller cone bit need not be perfectly conical (nor perfectly frustroconical), but often have a slightly swollen axial profile. Moreover, the axes of the cones do not have to intersect the centerline of the borehole. (The angular difference is referred to as the "offset" angle.) Another variable is the angle by which the centerline of the bearings intersects the horizontal plane of the bottom of the hole, and this angle is known as the journal angle. Thus as the drill bit is rotated, the cones typically do not roll true, and a certain amount of gouging and scraping takes place. The gouging and scraping action is complex in nature, and varies in magnitude and direction depending on a number of variables.

Conventional roller cone bits can be divided into two broad categories: Insert bits and steel-tooth bits. Steel tooth bits are utilized most frequently in softer formation drilling, whereas insert bits are utilized most frequently in medium and hard formation drilling.

Steel-tooth bits have steel teeth formed integral to the cone. (A hard facing is typically applied to the surface of the teeth to improve the wear resistance of the structure.) Insert bits have very hard inserts (e.g. specially selected grades of tungsten carbide) pressed into holes drilled into the cone surfaces. The inserts extend outwardly beyond the surface of the cones to form the "teeth" that comprise the cutting structures of the drill bit.

The design of the component elements in a rock bit are interrelated (together with the size limitations imposed by the overall diameter of the bit), and some of the design parameters are driven by the intended use of the product. For example, cone angle and offset can be modified to increase or decrease the amount of bottom hole scraping. Many other design parameters are limited in that an increase in one parameter may necessarily result in a decrease of another. For example, increases in tooth length may cause interference with the adjacent cones.

Background: Tooth Design

The teeth of steel tooth bits are predominantly of the inverted "V" shape. The included angle (i.e. the sharpness of the tip) and the length of the tooth will vary with the design of the bit. In bits designed for harder formations the teeth will be shorter and the included angle will be greater. Gage row teeth (i.e. the teeth in the outermost row of the cone, next to the outer diameter of the borehole) may have a "T" shaped crest for additional wear resistance.

The most common shapes of inserts are spherical, conical, and chisel. Spherical inserts have a very small protrusion and are used for drilling the hardest formations. Conical inserts have a greater protrusion and a natural resistance to breakage, and are often used for drilling medium hard formations.

Chisel shaped inserts have opposing flats and a broad elongated crest, resembling the teeth of a steel tooth bit. Chisel shaped inserts are used for drilling soft to medium formations. The elongated crest of the chisel insert is normally oriented in alignment with the axis of cone rotation. Thus, unlike spherical and conical inserts, the chisel insert may be directionally oriented about its center axis. (This is true of any tooth which is not axially symmetric.) The axial angle of orientation is measured from the plane intersecting the center of the cone and the center of the tooth.

Background: Bottom Hole Analysis

The economics of drilling a well are strongly reliant on rate of penetration. Since the design of the cutting structure of a drill bit controls the bit's ability to achieve a high rate of penetration, cutting structure design plays a significant role in the overall economics of drilling a well.

It has long been desirable to predict the development of bottom hole patterns on the basis of the controllable geometric parameters used in drill bit design, and complex mathematical models can simulate bottom hole patterns to a limited extent. To accomplish this it is necessary to understand first, the relationship between the tooth and the rock, and second, the relationship between the design of the drill bit and the movement of the tooth in relation to the rock. It is also known that these mechanisms are interdependent.

To better understand these relationships, much work has been done to determine the amount of rock removed by a single tooth of a drill bit. As can be seen by the forgoing discussion, this is a complex problem. For many years it has been known that rock failure is complex, and results from the many stresses arising from the combined movements and actions of the tooth of a rock bit. (Sikarskie, et al, PENETRATION PROBLEMS IN ROCK MECHANICS, ASME Rock Mechanics Symposium, 1973). Subsequently, work was been done to develop quantitative relationships between bit design and tooth-formation interaction. This has been accomplished by calculating the vertical, radial and tangential movement of the teeth relative to the hole bottom, to accurately represent the gouging and scrapping acfion of the teeth on roller cone bits. (Ma, A NEW WAY TO CHARACTERIZE THE GOUGING-SCRAPPING ACTION OF ROLLER CONE BITS, Society of Petroleum Engineers No. 19448, 1989). More recently, computer programs have been developed which predict and simulate the bottom hole patterns developed by roller cone bits by combining the complex movement of the teeth with a model of formation failure. (Ma, THE COMPUTER SIMULATION OF THE INTERACTION BETWEEN THE ROLLER BIT AND ROCK, Society of Petroleum Engineers No. 29922, 1995). Such formation failure models include a ductile model for removing the formation occupied by the tooth during its movement across the bottom of the hole, and a fragile breakage model to represent the surrounding breakage.

Currently, roller cone bit designs remain the result of generations of modifications made to original designs. The modifications are based on years of experience in evaluating bit run records and dull bit conditions. Since drill bits are run under harsh conditions, far from view, and to destruction, it is often very difficult to determine the cause of the failure of a bit. Roller cone bits are often disassembled in manufacturers' laboratories, but most often this process is in response to a customer's complaint regarding the product, when a verification of the materials is required. Engineers will visit the lab and attempt to perform a forensic analysis of the remains of a rock bit, but with few exceptions there is generally little evidence to support their conclusions as to which component failed first and why. Since rock bits are run on different drilling rigs, in different formations, under different operating conditions, it is extremely difficult draw conclusion from the dull conditions of the bits. As a result, evaluating dull bit conditions, their cause, and determinig design solutions is a very subjective process. What is known is that when the cutting structure or bearing system of a drill bit fails prematurely, it can have a serious detrimental effect of the economics of drilling.

Though numerical methods are now available to model the bottom hole pattern produced by a roller cone bit, there is no suggestion as to how this should be used to improve the design of the bits other than to predict the presence of obvious problems such as tracking. For example, the best solution available for dealing with the problems of lateral vibration, is a recommendation that roller cone bits should be run at low to moderate rotary speeds when drilling medium to hard formations to control bit vibrations and prolong life, and to use downhole vibration sensors. (Dykstra, et al, EXPERIMENTAL EVALUATIONS OF DRILL STRING DYNAMICS, Amoco Report Number F94-P-80, 1994).

Force-Balanced Roller-Cone Bits, Systems, Drilling Methods, and Design Methods

The present application describes improved methods for designing roller cone bits, as well as improved drilling methods, and drilling systems. The present application teaches that roller cone bit designs should have equal mechanical downforce on each of the cones. This is not trivial: without special design consideration, the weight on bit will NOT automatically be equalized among the cones.

Roller-cone bits are normally NOT balanced, for several reasons:

Asymmetric cutting structures. Usually the rows on cones are intermeshed in order to cover fully the hole bottom and have a self-clearance effects. Therefore, even the cone shapes may be the same for all three cones, the teeth row distributions on cones are different from cone to cone. The number of teeth on cones are usually different. Therefore, the cone having more row and more teeth than other two cones may remove more rock and as a results, may spent more energy (Energy Imbalance). An energy imbalance usually leads to bit force imbalance.

Offset effects. Because of the offset, a scraping motion will be induced. This scraping motion is different from teeth row to teeth row and as a result, the scraping force (tangent force) acting on teeth is different from row to row. This will generate an imbalance force on bit.

Tracking effects. If at least one of the cones is in tracking, then this cone will gear with the hole bottom without penetration, the rock not removed by this cone will be partly removed by other two cones. As a result, the bit is unbalanced.

The applicant has discovered, and has experimentally verified, that equalization of downforce per cone is a very important (and greatly underestimated) factor in roller cone performance. Equalized downforce is believed to be a significant factor in reducing gyration, and has been demonstrated to provide substantial improvement in drilling efficiency. The present application describes bit design procedures which provide optimization of downforce balancing as well as other parameters.

A roller-cone bit will always be a strong source of vibration, due to the sequential impacts of the bit teeth and the inhomogeneities of the formation. However, many results of this vibration are undesirable. It is believed that the improved performance of balanced-downforce cones is partly due to reduced vibration.

Any force imbalance at the cones corresponds to a bending torque, applied to the bottom of the drill string, which rotates with the drill string. This rotating bending moment is a driving force, at the rotary frequency, which has the potential to couple to oscillations of the drill string. Moreover, this rotating bending moment may be a factor in biasing the drill string into a regime where vibration and instabilities are less heavily damped. It is believed that the improved performance of balanced-downforce cones may also be partly due to reduced oscillation of the drill string.

The disclosed innovations, in various embodiments, provide one or more of at least the following advantages:.

The roller cone bit is force balanced such that axial loading between the arms is substantially equal.

The roller cone bit is energy balanced such that each of the cutting structures drill substantially equal volumes of formation.

The drill bit has decreased axial and lateral operating vibration.

The cutting structures, bearings, and seals have increased lifetime and improved performance and durability.

Drill string life is extended.

The roller cone bit has minimized tracking of cutting structures, giving improved performance and extending cutting structure life.

The roller cone bit has an optimized number of teeth in a given formation area.

Bit performance is improved.

Off-center rotation is minimized.

The roller cone bit has optimized (minimized and equalized) uncut formation ring width.

Energy balanced roller cone bits can be further optimized by minimizing cone and bit tracking.

Energy balanced roller cone bits can be further optimized by minimizing and equalizing uncut formation rings.

Designer can evaluate the force balance and energy balance conditions of existing bit designs.

Designer can design force balanced drill bits with predictable bottom hole patterns without relying on lab tests followed by design modifications.

Designer can optimize the design of roller cone drill bits within designer-chosen constraints.

Other advantages of the various disclosed inventions will become apparent from the following descriptions, taken in connection with the accompanying drawings, wherein, by way of illustration and example, a sample embodiment is disclosed.

U.S. patent application Ser. No. 09/387,304, filed Aug. 31, 1999, entitled "Roller-Cone Bits, Systems, Drilling Methods, and Design Methods with Optimization of Tooth Orientation" (Atty. Docket No. SC-98-26), now U.S. Pat. No. 6,095,262 and claiming priority from U.S. Provisional Application No. 60/098,442 filed Aug. 31 1998, describes roller cone drill bit design methods and optimizations which can be used separately from or in synergistic combination with the methods disclosed in the present application. That application, which has common ownership, inventorship, and effective filing date with the present application, and its provisional priority application, are both hereby incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWING

The disclosed inventions will be described with reference to the accompanying drawings, which show important sample embodiments of the invention and which are incorporated in the specification hereof by reference, wherein:

FIG. 1 shows an element and how the tooth is divided into elements for tooth force evaluation.

FIG. 2 diagrammatically shows a roller cone and the bearing forces which are measured in the current disclosure.

FIG. 3 shows the four design variables of a tooth on a cone.

FIG. 4 shows the bottom hole pattern generated by a steel tooth bit.

FIG. 5 shows the layout of row distribution in a plane showing the distance between any two tooth surfaces.

FIG. 6 shows a flowchart of the optimization procedure to design a force balanced bit.

FIGS. 7A–C compare the three cone profiles before and after optimization.

FIGS. 8A–B compare the bottom hole pattern before and after optimization.

FIGS. 9A–B compare the cone layout before and after optimization.

FIG. 10 shows an example of a drill rig which can use bits designed by the disclosed method.

FIG. 11 shows an example of a roller cone bit.

FIG. 12 shows an example of a drag bit.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The numerous innovative teachings of the present application will be described with particular reference to the presently preferred embodiment (by way of example, and not of limitation).

Rock Bit Computer Model

The present invention uses a single element force-cutting relationship in order to develop the total force-cutting relationship of a cone and of an entire roller cone bit. Looking at FIG. 1, each tooth, shown on the right side, can be thought of as composed of a collection of elements, such as are shown on the left side. Each element used in the present invention has a square cross section with area S_e (its cross-section on the x-y plane) and length L_e (along the z axis). The force-cutting relationship for this single element may be described by:

$$F_{zr}=K_r*\sigma*S_r \quad (1)$$

$$F_{xr}=\mu_x*F_{zr} \quad (2)$$

$$F_{yr}=\mu_y*F_{zr} \quad (3)$$

where F_{zr} is the normal force and F_{xr}, F_{yr} are side forces, respectively, σ is the compressive strength, S_r the cutting depth and k_r, μ_x and μ_y are coefficient associated with formation properties. These coefficients may be determined by lab test. A tooth or an insert can always be divided into several elements. Therefore, the total force on a tooth can be obtained by integrating equation (1) to (3). The single element force model used in the invention has significant advantage over the single tooth or single insert model used in most of the publications. The only way to obtain a force model is by lab test. There are many types of inserts used today for roller cone bit depending on the rock type drilled. If the single insert force model is used, a lot of tests have to be done and this is very difficult if not impossible. By using the element force model, only a few tests may be enough because any kind of insert or tooth can be always divided into elements. In other words, one element model may be applied to all kinds of inserts or teeth.

After having the single element force model, the next step is to determine the interaction between inserts and the formation drilled. This step involves the determination of the tooth kinematics (local) from the bit and cone kinematics (global) as described below.

(1) The bit kinematics is described by bit rotation speed, Ω=RPM (revolutions per minute), and the rate of penetration, ROP. Both RPM and ROP may be considered as constant or as function with time.

(2) The cone kinematics is described by cone rotational speed. Each cone may have its own speed. The initial value is calculated from the bit geometric parameters or just estimated from experiment. In the calculation the cone speed may be changed based on the torque acting on the cone.

(3) At the initial time, t0, the hole bottom is considered as a plane and is meshed into small grids. The tooth is also meshed into grids (single elements). At any time t, the position of a tooth in space is fully determined. If the tooth is in interaction with the hole bottom, the hole bottom is updated and the cutting depth for each cutting element is calculated and the forces acting on the elements are obtained.

(4) The element forces are integrated into tooth forces, the tooth forces are integrated into cone forces, the cone forces are transferred into bearing forces and the bearing forces are integrated into bit forces.

(5) After the bit is fully drilled into the rock, these forces are recorded at each time step. A period time usually at least 10 seconds is simulated. The average forces may be considered as static forces and are used for evaluation of the balance condition of the cutting structure.

Evaluation of A Force Balanced Roller Cone Bit

The applied forces to bit are the weight on bit (WOB) and torque on bit (TOB). These forces will be taken by three cones. Due to the asymmetry of bit geometry, the loads on three cones are usually not equal. In other words, one of the three cones may do much more work than other two cones. With reference to FIG. 2, the balance condition of a roller cone bit may be evaluated using the following criteria:

$$\mathrm{Max}(\omega1, \omega2, \omega3)-\mathrm{Min}(\omega1, \omega2, \omega3)<=\omega0 \quad (4)$$

$$\mathrm{Max}(\eta1, \eta2, \eta3)-\mathrm{Min}(\eta1, \eta2, \eta3)<=\eta0 \quad (5)$$

$$\mathrm{Max}(\lambda1, \lambda2, \lambda3)-\mathrm{Max}(\lambda1, \lambda2, \lambda3)<=\lambda0 \quad (6)$$

$$\xi=F_r/WOB*100\%<=\xi0 \quad (7)$$

where ωi (i=1,2,3) is defined by ωi=WOBi/WOB*100%. WOBi is the weight on bit taken by cone i. ηi is defined by ηi=Fzi/ΣFzi*100% with Fzi being the i-th cone axial force. And λi is defined by λi=Mzi/ΣMzi*100% with Mzi being the i-th cone moment in the direction perpendicular to i-th cone axis. Finally ξ is the bit imbalance force ratio with Fr being the bit imbalance force. A bit is perfectly balanced if:

$$\omega1=\omega2\ \omega=\omega3=33.333\%\ \text{or}\ \omega=0.0\%$$

$$\eta1=\eta2=\eta3=33.333\%\ \text{or}\ \eta0=0.0\%$$

$$\lambda1=\lambda2=\lambda3=33.333\%\ \text{or}\ \lambda0=0.0\%$$

$$\xi=0.0\%$$

In most cases if ω0, η0, λ0, ξ0 are controlled with some limitations, the bit is balanced. The values of ω0, η0, λ0, ξ0 depend on bit size and bit type.

There is a distinction between force balancing techniques and energy balancing. A force balanced bit uses multiple objective optimization technology, which considers weight on bit, axial force, and cone moment as separate optimization objectives. Energy balancing uses only single objective optimization, as defined in equation (11) below.

Design of A Force Balanced Roller Cone Bit

As we stated in previous sections, there are many parameters which affect bit balance conditions. Among these parameters, the teeth crest length, their positions on cones (row distribution on cone) and the number of teeth play a significant role. An increase in the size of any one parameter must of necessity result in the decrease or increase of one or more of the others. And in some cases design rules may be violated. Obviously the development of optimization procedure is absolutely necessary.

The first step in the optimization procedure is to choose the design variables. Consider a cone of a steel tooth bit as shown in FIG. 3. The cone has three rows. For the sake of simplicity, the journal angle, the offset and the cone profile will be fixed and will not be as design variables. Therefore the only design variables for a row are the crest length, Lc, the radial position of the center of the crest length, Rc, and the tooth angles, α and δ. Therefore, the number of design variables is 4 times of the total number of rows on a bit.

The second step in the optimization procedure is to define the objectives and express mathematically the objectives as function of design variables. According to equation (1), the force acting on an element is proportional to the rock volume removed by that element. This principle also applies to any tooth. Therefore, the objective is to let each cone remove the same amount of rock in one bit revolution. This is called volume balance or energy balance. The present inventor has found that an energy balanced bit will lead to force balanced in most cases. Consider FIG. 4 which shows the patterns cut by each cone on the hole bottom. The first rows of all three cones have overlap and the inner rows remove the rock independently. Suppose the bit has a cutting depth Δ in one bit revolution. It is not difficult to calculate the volumes removed by each row and the volume matrix may have the form:

$$V=[V_{ij}],\ i=1,2,3;\ j=1,2,3,4. \quad (8)$$

where i represent the cone number andj the row number. For example, V_{32} is the element in the volume matrix representing the rock volume removed by the second row of the third cone. The elements V_{ij} of this matrix are all functions of the design variables.

In reality, the removed volume by each row depends not only on the above design variables, but also on the number of teeth on that row and the tracking condition. Therefore the volume matrix calculated in a 2D manner must be scaled. The scale matrix, K_v, may be obtained as follows.

$$K_v(i,j)=V_{3d0}(i,j)/V_{2d0}(i,j) \quad (9)$$

where V_{3d0} is the volume matrix of the initial designed bit (before optimization). V_{3d0} is obtained from the rock bit computer program by simulate the bit drilling procedure at least 10 seconds. V_{2d0} is the volume matrix associated with the initial designed matrix and obtained using the 2D manner based on the bottom pattern shown in FIG. 4. The volume matrix has the final form:

$$V_b(i,j)=K(i,j)*V(i,j)=f_v(L_c, R_c, \alpha, \beta) \quad (10)$$

Let V_1, V_2 and V_3 be the volume removed by cone 1,2 and 3, respectively. For the energy balance, the objective function takes the following form:

$$Obj=(V_1-V_m)^2+(V_2-V_m)^2+(V_3-V_m)^2 \quad (11)$$

where $V_m=(V_1+V_2+V_3)/3$;

The third step in the optimization procedure is to defme the bounds of the design variables and the constraints. The lower and upper bounds of design variables can be determined by requirements on element strength and structural limitation. For example, the lower bound of a tooth crest length is determined by the tooth strength. The angle α and β may be limited to 0–45 degrees. One of the most important constraints is the interference between teeth on different cones. A minimum -clearance between teeth surface must be kept. Consider FIG. 5 where cone profile is shown in a plane. A minimum clearance between tooth surfaces is required. This clearance can be expressed as a function of the design variables.

$$\Delta d=f_d(L_c, R_c, \alpha, \beta) \quad (12)$$

Another constraint is the width of the uncut formation rings on bottom. The width of the uncut formation rings should be minimized or equalized in order to avoid the direct contact of cone surface to formation drilled. These constraints can be expressed as:

$$\Delta w_{min}<=\Delta wi=fw_i(L_c, R_c, \alpha, \beta)<=\Delta w_{max} \quad (13)$$

There may be other constraints, for example, the minimum space between two neighbored rows on the same cone required by the mining process.

After having the objective function, the bounds and the constraints, the problem is simplified to a general nonlinear optimization problem with bounds and nonlinear constraints which can be solved by different methods. FIG. 6 shows the flowchart of the optimization procedure. The procedure begins by reading the bit geometry and other operational parameters. The forces on the teeth, cones, bearings, and bit are then calculated. Once the forces are known, they are compared, and if they are balanced, then the design is optimized. If the forces are not balanced, then the optimization must occur. Objectives, constraints, design variables and their bounds (maximum and minimum allowed values) are defined, and the variables are altered to conform to the new objectives. Once the new objectives are met, the new geometric parameters are used to redesign the bit, and the forces are again calculated and checked for balance. This process is repeated until the desired force balance is achieved.

As an example, FIGS. 7A–C show the row distributions on three cones of a 9" steel tooth bit before and after optimization. FIGS. 8A and 8B compare the bottom hole patterns cut by the different cones before and after optimization. FIGS. 9A and B compare the cone layouts before and after optimization.

In the preferred embodiment of the present disclosure, a roller cone bit is provided for which the volume of formation removed by each tooth in each row, of each cutting structure (cone), is calculated. This calculation is based on input data of bit geometry, rock properties, and operational parameters. The geometric parameters of the roller cone bit are then modified such that the volume of formation removed by each cutting structure is equalized. Since the amount of formation removed by any tooth on a cutting structure is a function of the force imparted on the formation by the tooth, the volume of formation removed by a cutting structure is a direct function of the force applied to the cutting structure. By balancing the volume of formation removed by all cutting structures, force balancing is also achieved.

As another feature of the preferred embodiment, a roller cone bit is provided for which the width of the rings of formation remaining uncut is calculated, as it remains between the rows of the intermeshing teeth of the different cutting structures. The geometric parameters of the roller cone bit are then modified such that the width of the uncut area for each row is substantially minimized and equalized within selected acceptable limits. By minimizing the uncut rings on the bottom of the hole, the bit will be able to crush the uncut rings upon successive rotations due to the craters of formation removed immediately adjacent to the uncut rings. By equalizing the width of the uncut rings, the force required to crush the rings will be even from any point on the hole face, such that as cutting elements (teeth) engage the rings on successive rotations, the rings act to uniformly retain the bit drilling on-enter.

According to a disclosed class of innovative embodiments, there is provided: A roller cone drill bit comprising: a plurality of arms; rotatable cutting structures mounted on respective ones of said arms; and a plurality of teeth located on each of said cutting structures; wherein approximately the same axial force is acting on each of said cutting structure.

According to another disclosed class of innovative embodiments, there is provided: A roller cone drill bit comprising: a plurality of arms; rotatable cutting structures mounted on respective ones of said arms; and a plurality of teeth located on each of said cutting structures; wherein a substantially equal volume of formation is drilled by each said cutting structure.

According to another disclosed class of innovative embodiments, there is provided: A rotary drilling system, comprising: a drill string which is connected to conduct drilling fluid from a surface location to a rotary drill bit; a rotary drive which rotates at least part of said drill string together with said rotary drill bit comprising a plurality of arms; rotatable cutting structures mounted on respective ones of said arms; and a plurality of teeth located on each of said cutting structures; wherein approximately the same axial force is acting on each said cutting structure.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone drill bit, comprising the steps of: (a) calculating the volume of formation cut by each tooth on each cutting structure; (b) calculating the volume of formation cut by each cutting structure per revolution of the drill bit; (c) comparing the volume of formation cut by each of said cutting structures with the volume of formation cut by all others of said cutting structures of the bit; (d) adjusting at least one geometric parameter on the design of at least one cutting structure; and (e) repeating steps (a) through (d) until substantially the same volume of formation is cut by each of said cutting structures of said bit.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone drill bit, the steps of comprising: (a) calculating the axial force acting on each tooth on each cutting structure; (b) calculating the axial force acting on each cutting structure per revolution of the drill bit; (c) comparing the axial force acting on each of said cutting structures with the axial force on the other ones of said cutting structures of the bit; (d) adjusting at least one geometric parameter on the design of at least one cutting structure; (e) repeating steps (a) through (d) until approximately the same axial force is acting on each cutting structure.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone drill bit, the steps of comprising: (a) calculating the force balance conditions of a bit; (b) defining design variables; (c) determine lower and upper bounds for the design variables; (d) defining objective functions; (e) defining constraint functions; (f) performing an optimization means; and, (g) evaluating an optimized cutting structure by modeling.

According to another disclosed class of innovative embodiments, there is provided: A method of using a roller cone drill bit, comprising the step of rotating said roller cone drill bit such that substantially the same volume of formation is cut by each roller cone of said bit.

According to another disclosed class of innovative embodiments, there is provided: A method of using a roller cone drill bit, comprising the step of rotating said roller cone drill bit such that substantially the same axial force is acting on each roller cone of said bit.

Modifications and Variations

As will be recognized by those skilled in the art, the innovative concepts described in the present application can be modified and varied over a tremendous range of applications, and accordingly the scope of patented subject matter is not limited by any of the specific exemplary teachings given.

Additional general background, which helps to show the knowledge of those skilled in the art regarding implementations and the predictability of variations, may be found in the following publications, all of which are hereby incorporated by reference: APPLIED DRILLING ENGINEERING, Adam T. Bourgoyne Jr. et aL, Society of Petroleum Engineers Textbook series (1991), OIL AND GAS FIELD DEVELOPMENT TECHNIQUES: DRILLING, J.-P. Nguyen (translation 1996, from French original 1993), MAKING HOLE (1983) and DRILLING MUD (1984), both part of the Rotary Drilling Series, edited by Charles Kirkley.

None of the description in the present application should be read as implying that any particular element, step, or function is an essential element which must be included in the claim scope: THE SCOPE OF PATENTED SUBJECT MATTER IS DEFINED ONLY BY THE ALLOWED CLAIMS. Moreover, none of these claims are intended to invoke paragraph six of 35 USC section 112 unless the exact words "means for" are followed by a participle.

What is claimed is:

1. A roller cone drill bit comprising:

a plurality of arms;

rotatable cutting structures mounted on respective ones of said arms; and

a plurality of teeth located on each of said cutting structures, wherein the number and locations of said teeth are not identical between ones of said rotatable cutting structures;

wherein approximately the same axial force is acting on each of said cutting structure.

2. The roller cone drill bit of claim 1, wherein the axial force on each of said cutting structure is between thirty-one (31) percent and thirty-five (35) percent of the total of the axial force on the bit.

3. A roller cone drill bit comprising:

a plurality of arms;

rotatable cutting structures mounted on respective ones of said arms; and

a plurality of teeth located on each of said cutting structures, wherein the number and locations of said teeth are not identical between ones of said rotatable cutting structures;

wherein a substantially equal volume of formation is drilled by each said cutting structure.

4. The roller cone drill bit of claim 3, wherein the volume of formation drilled by each of said cutting structures is between thirty-one (31) percent and thirty-five (35) percent of the total volume drilled by the drill bit.

5. A rotary drilling system, comprising:

a drill string which is connected to conduct drilling fluid from a surface location to a rotary drill bit;

a rotary drive which rotates at least part of said drill string together with said bit

said rotary drill bit comprising

a plurality of arms;

rotatable cutting structures mounted on respective ones of said arms; and

a plurality of teeth located on each of said cutting structures, wherein the number and locations of said teeth are not identical between ones of said rotatable cutting structures;

wherein approximately the same axial force is acting on each of said cutting structure.

6. A method of designing a roller cone drill bit, comprising the steps of:

(a) calculating the volume of formation cut by each tooth on each cutting structure;

(b) calculating the volume of formation cut by each cutting structure per revolution of the drill bit;

(c) comparing the volume of formation cut by each of said cutting structures with the volume of formation cut by all others of said cutting structures of the bit;

(d) adjusting at least one geometric parameter on the design of at least one cutting structure; and

(e) repeating steps (a) through (d) until substantially the same volume of formation is cut by each of said cutting structures of said bit.

7. The method of claim 6, wherein the step of calculating the volume of formation cut by each tooth on each cutting structure further comprises the step of using numerical simulation to determine the interval progression of each tooth as it intersects the formation.

8. A method of designing a roller cone drill bit, the steps of comprising:

(a) calculating the axial force acting on each tooth on each cutting structure;

(b) calculating the axial force acting on each cutting structure per revolution of the drill bit;

(c) comparing the axial force acting on each of said cutting structures with the axial force on the other ones of said cutting structures of the bit;

(d) adjusting at least one geometric parameter on the design of at least one cutting structure;

(e) repeating steps (a) through (d) until approximately the same axial force is acting on each cutting structure.

9. The method of claim 8, wherein the step of calculating the normal force acting on each tooth, on each cutting structure further comprises the step of using numerical simulation to determine the interval progression of each tooth as it intersects the formation.

10. The method of claim 8, further comprising the steps of:

(a) calculating the volume of formation displaced by the depth of penetration of each tooth;

(b) calculating the volume of formation displaced by the tangential scrapping movement of each tooth;

(c) calculating the volume of formation displaced by the radial scrapping movement of each tooth; and,

(d) calculating the volume of formation displaced by a crater enlargement parameter function.

11. A method of using a roller cone drill bit which has at least two roller cones which are not identical to each other, comprising the step of rotating said roller cone drill bit such that substantially the same volume of formation is cut by each roller cone of said bit.

12. A method of using a roller cone drill bit which has at least two roller cones which are not identical to each other, comprising the step of rotating said roller cone drill bit such that substantially the same axial force is acting on each roller cone of said bit.

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US006401839B1

(12) **United States Patent**
Chen

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(45) **Date of Patent: Jun. 11, 2002**

(54) **ROLLER CONE BITS, METHODS, AND SYSTEMS WITH ANTI-TRACKING VARIATION IN TOOTH ORIENTATION**

(75) Inventor: **Shilin Chen**, Plano, TX (US)

(73) Assignee: **Halliburton Energy Services, Inc.**, Carrollton, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(22) Filed: **Mar. 10, 2000**

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/387,304, filed on Aug. 31, 1999, now Pat. No. 6,095,262.

(60) Provisional application No. 60/098,442, filed on Aug. 31, 1998.

(51) **Int. Cl.**^{7} **E21B 10/16**

(52) **U.S. Cl.** 175/57; 175/374; 175/376; 175/378; 76/108.2

(58) **Field of Search** 175/374, 376, 175/377, 378, 426, 57; 76/108.2

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,334,586 A	*	6/1982	Schumacher	175/374
4,343,371 A	*	8/1982	Baker, III et al.	175/336
4,393,948 A	*	7/1983	Fernandez	175/373
5,197,555 A	*	3/1993	Estes	175/431
5,224,560 A	*	7/1993	Fernandez	175/374
6,095,262 A	*	8/2000	Chen	175/57
6,241,034 B1	*	6/2001	Teinke et al.	175/331

* cited by examiner

Primary Examiner—Hoang Dang
(74) *Attorney, Agent, or Firm*—Groover & Associates; Robert Groover

(57) **ABSTRACT**

A roller cone drill bit in which the orientations of the teeth are varied within a single row, and/or between the heel row of one cone and the heel row of another cone, to prevent tracking.

11 Claims, 5 Drawing Sheets

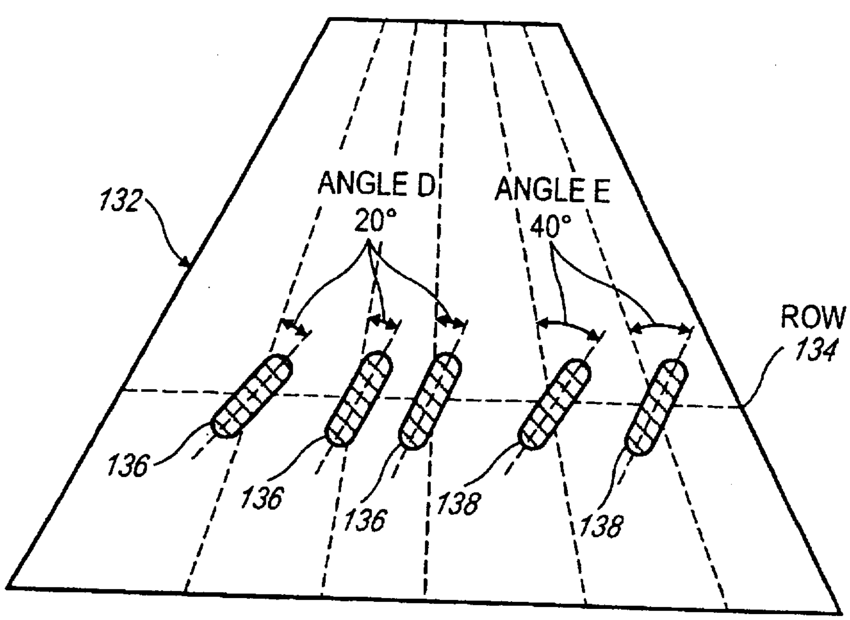


EXHIBIT A3

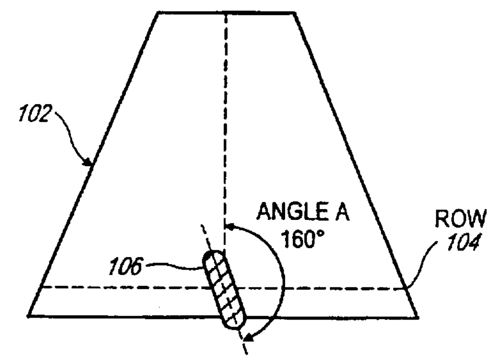


FIG. 1A

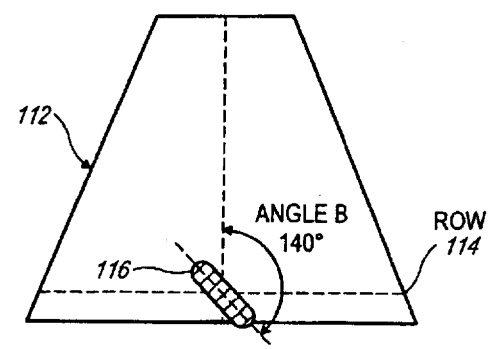


FIG. 1B

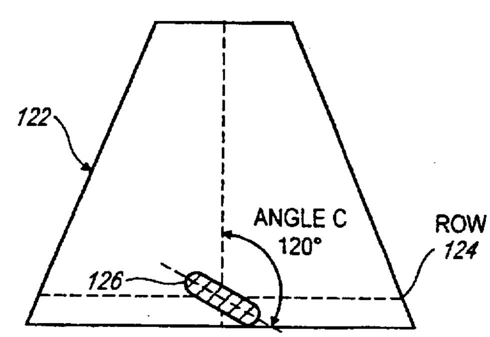


FIG. 1C

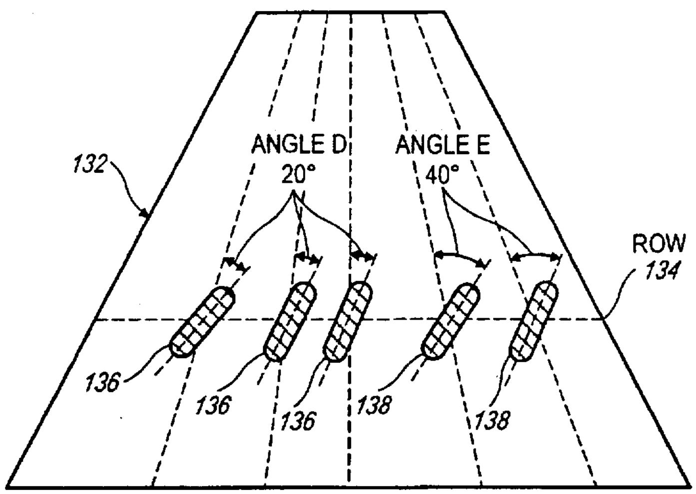


FIG. 1D

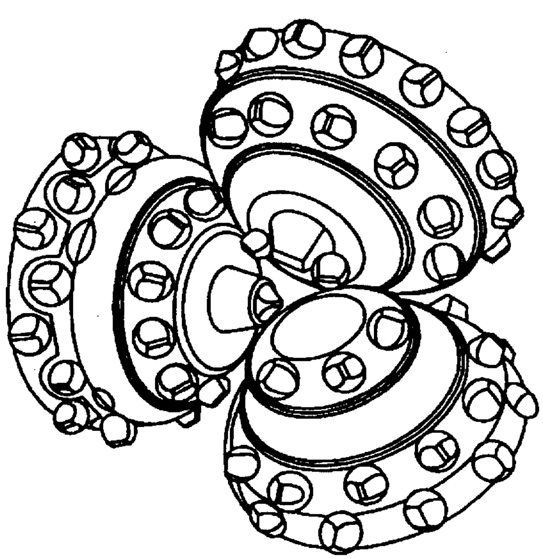


FIG. 2

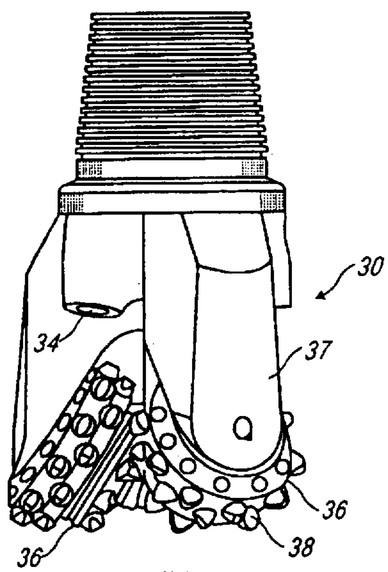


FIG. 3
(PRIOR ART)

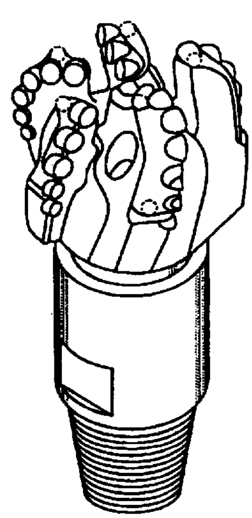


FIG. 4
(PRIOR ART)

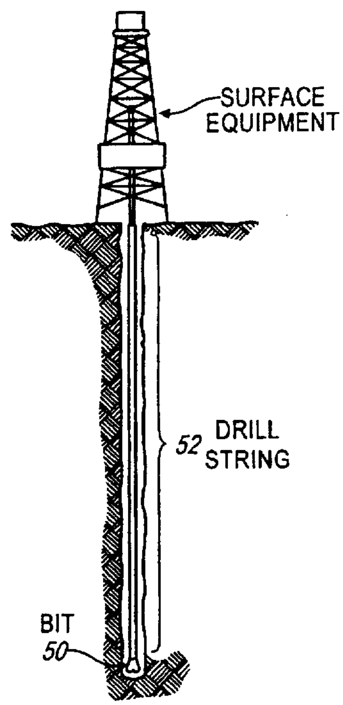
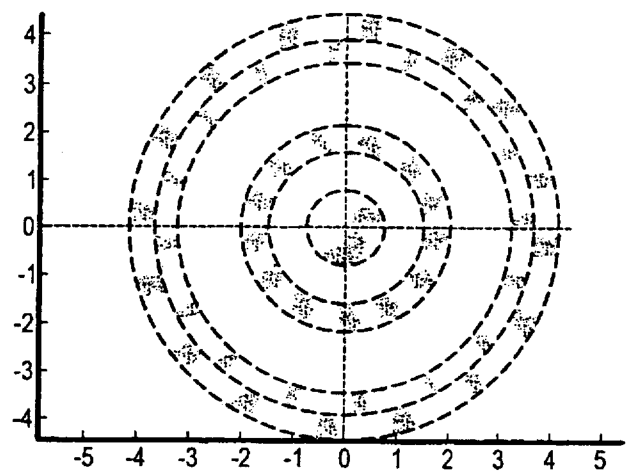
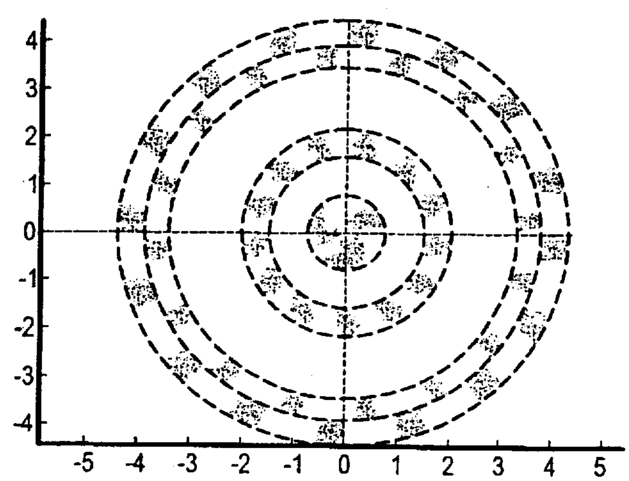


FIG. 5
(PRIOR ART)



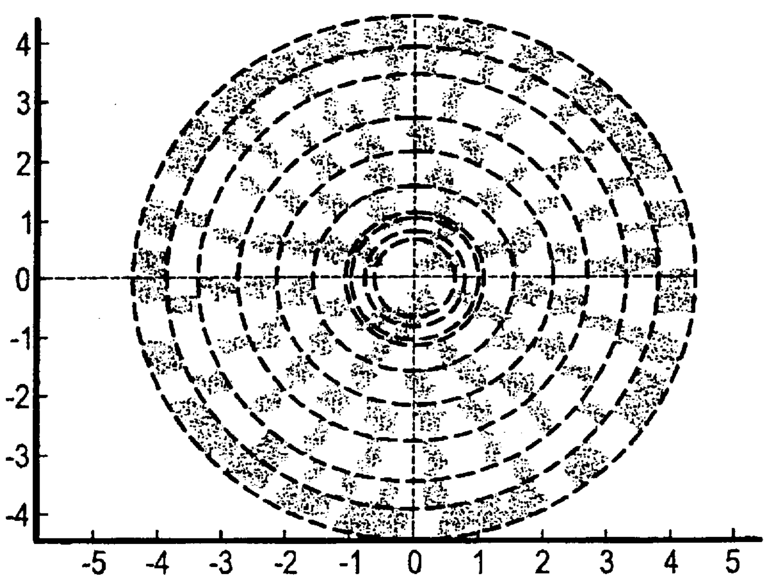
Cone: 1; Bit: era22d; Bit RPM=60; ROP=10ft/h;
Cone RPM=86.7591; Cut area=11.047%

FIG. 6A



Cone: 1; Bit: era22d; Bit RPM=60; ROP=10ft/h;
Cone RPM=86.7591; Cut area=16.0792%

FIG. 6B



Cone: 1; Bit: era22d; Bit RPM=60; ROP=10ft/h; Cone RPM=86.7591; Cut area=11.047%

FIG. 6C

ROLLER CONE BITS, METHODS, AND SYSTEMS WITH ANTI-TRACKING VARIATION IN TOOTH ORIENTATION

CROSS-REFERENCE TO OTHER APPLICATION

This application is a continuation-in-part of U.S. application Ser. No. 09/387,304 filed Aug. 31, 1999 (now issued as U.S. Pat. No. 6,095,262), and therethrough claims priority from U.S. provisional application 60/098,442 filed Aug. 31, 1998, which is hereby incorporated by reference.

BACKGROUND AND SUMMARY OF THE INVENTION

The present invention relates generally to the drilling of oil and gas wells, or similar drilling operations, and in particular to orientation of tooth angles on a roller cone drill bit.

Background: Rotary Drilling

Oil wells and gas wells are drilled by a process of rotary drilling, using a drill rig such as is shown in FIG. 5. In conventional vertical drilling, a drill bit **50** is mounted on the end of a drill string **52** (drill pipe plus drill collars), which may be miles long, while at the surface a rotary drive (not shown) turns the drill string, including the bit at the bottom of the hole.

Two main types of drill bits are in use, the fixed or drag bit, seen in FIG. **4**, and the roller cone bit, seen in FIG. 3. In the roller cone bit a set of cones **36** (two are visible in this drawing) having teeth or cutting inserts **38** are arranged on rugged bearings on the arms **37** of the bit. As the drill string is rotated, the cones will roll on the bottom of the hole, and the teeth or cutting inserts will crush the formation beneath them. Drilling fluid, which is pumped down the drill string under pressure, is directed out nozzles **34**, to provide cleaning of the bit and to sweep broken fragments of rock uphole.

Background: Roller Cone Bit Design

FIG. 2 is view from the bottom of a roller cone bit which has three cones **201**, **202**, and **203**, each containing rows of chisel-shaped inserts **210** for cutting elements. It can be noted that the "cones" in a roller cone bit need not be perfectly conical (nor perfectly frustroconical), but often have a slightly swollen axial profile. Moreover, the axes of the cones do not have to intersect the centerline of the borehole, as can be seen in this drawing. (The angular difference is referred to as the "offset" angle.) Another variable is the angle by which the centerline of the bearings intersects the horizontal plane of the bottom of the hole, and this angle is known as the journal angle. Thus as the drill bit is rotated, the cones typically do not roll true, and a certain amount of gouging and scraping takes place. The gouging and scraping action is complex in nature, and varies in magnitude and direction depending on a number of variables.

It should also be noted that while each cone has a row of teeth circumscribing its greatest circumference (this is the heel, or gage, row), the other rows of teeth are offset so that no two cones have teeth which will intersect each other as they rotate.

Conventional roller cone bits can be divided into two broad categories: Insert bits and steel-tooth bits. Steel tooth bits are utilized most frequently in softer formation drilling, whereas insert bits are utilized most frequently in medium and hard formation drilling.

Steel-tooth bits have steel teeth formed integral to the cone. (A hard-facing is typically applied to the surface of the teeth to improve the wear resistance of the structure.) Insert bits have very hard inserts (e.g. specially selected grades of tungsten carbide) press-fitted into holes drilled into the cone surfaces. The inserts extend outwardly beyond the surface of the cones to form the "teeth" that comprise the cutting structures of the drill bit.

The design of the component elements in a rock bit are interrelated (together with the size limitations imposed by the overall diameter of the bit), and some of the design parameters are driven by the intended use of the product. For example, cone angle and offset can be modified to increase or decrease the amount of bottom hole scraping. Many other design parameters are limited in that an increase in one parameter may necessarily result in a decrease of another. For example, increases in tooth length may cause interference with the adjacent cones.

Background: Tooth Design

The teeth of steel tooth bits are predominantly of the inverted "V" shape. The included angle (i.e. the sharpness of the tip) and the length of the tooth will vary with the design of the bit. In bits designed for harder formations the teeth will be shorter and the included angle will be greater. Gage row teeth (i.e. the teeth in the outermost row of the cone, next to the outer diameter of the borehole) may have a "T" shaped crest for additional wear resistance.

The most common shapes of inserts are spherical, conical, and chisel. Spherical inserts have a very small protrusion and are used for drilling the hardest formations. Conical inserts have a greater protrusion and a natural resistance to breakage, and are often used for drilling medium hard formations.

Chisel shaped inserts have opposing flats and a broad elongated crest, resembling the teeth of a steel tooth bit. Chisel shaped inserts are used for drilling soft to medium formations. The elongated crest of the chisel insert is normally oriented in alignment with the axis of cone rotation, as can be seen in FIG. 2. Thus, unlike spherical and conical inserts, the chisel insert may be directionally oriented about its center axis. (This is true of any tooth which is not axially symmetric.) The angle of orientation is measured as a deviation from the plane intersecting the center of the cone and the center of the tooth.

Background: Roller Cone Tracking

The study of bottom hole patterns has allowed engineers to evaluate performance and to begin to reduce such phenomena as tracking. FIG. 6A shows a computer generated pattern of the impressions of the teeth of a single roller cone on the hole bottom after a single revolution of the bit, showing a large separation between the individual teeth impressions, and between the rows on the cone.

FIG. 6C shows the impression of all of the cones on the bit after a single revolution of the bit. Note that while the inner rows of teeth from different cones do not generally follow the same path as they traverse the hole bottom, the teeth in the heel row of all of the cones tend to follow a single path on the outer circumference of the hole.

Tracking occurs when the teeth of a drill bit fall into the impressions in the formation formed by other teeth at a preceding moment in time during the revolution of the drill bit. FIG. 6B shows an impression of a single cone on the hole bottom after two revolutions of the bit. In this case, many of the impressions from the first revolution are partially overlain by the impressions of that same row from the second revolution. This overlapping will put lateral pressure on the teeth, tending to cause the cone to align with the previous impressions. Tracking can also happen when teeth of one cone's heel row fall into the impressions made by the teeth of another cone's heel row. Tracking results in slow rates of penetration, detrimental wear of the cutting structures and premature failure of bits.

Background: Bit Design to Prevent Tracking

The economics of drilling a well are strongly reliant on rate of penetration, which is itself strongly affected by the design of the cutting structures. Currently, roller cone bit designs remain the result of generations of modifications made to original designs. The modifications are based on years of experience in evaluating bit records, dull bit conditions, and bottom hole patterns, but these bit designs have not solved the issue of tracking.

One method commonly used to discourage bit tracking is known as a staggered tooth design. In this design the teeth are located at unequal intervals along the circumference of the cone. This is intended to interrupt the recurrent pattern of impressions on the bottom of the hole. However, staggered tooth designs do not prevent tracking of the outermost rows of teeth, where the teeth are encountering impressions in the formation left by teeth on other cones. Staggered tooth designs also have the short-coming that they can cause fluctuations in cone rotational speed and increased bit vibration.

U.S. Pat. No. 5,197,555 to Estes discloses milled-tooth cones with "the gage [row] of one cone oblique to the leading side and the gage row of another cone oblique to the trailing side".

Roller Cone Bits, Methods, and Systems with Anti-Tracking Variation in Tooth Orientation

The present application discloses new bit and cone designs, as well as methods of design and systems and drilling methods using these designs, in which variation in tooth orientation is used to reduce tracking. (Of course, tooth orientation is only relevant if the teeth are not axisymmetric, e.g. with chisel shaped insert teeth.) At least two classes of embodiments are disclosed, which can be used separately or (to achieve a synergistic result) together.

The parent application described bit design procedures using control of tooth orientation as one of the design variables. In implementing those procedures, the present inventor realized that the variation in tooth orientation which is described in that application can also achieve a substantial improvement in tracking resistance. When one tooth's intrusion into the formation partly overlaps the impression made by a preceding tooth, a lateral force will result which tends to align the intrusion with the impression. However, the present inventor has realized that, when a tooth's orientation does NOT allow it to fully fit into the impression made by a previous tooth, the lateral force tending to pull the tooth toward the impression will be reduced (though typically not eliminated). By varying tooth orientation to avoid perfect fit between an impression and a following tooth (in some cases), the propensity to track can be reduced. The less perfect the match between one tooth and another, the more the propensity to track is reduced; for example, with chisel-shaped teeth, the maximum reduction in lateral force is achieved if a tooth is 90 degrees out of alignment with a following tooth; but significant reductions can be achieved even with 30 degrees of misalignment.

Co-pending application Ser. No. 09/387,304, filed Aug. 31, 1999, now U.S. Pat. No. 6,095,262 and which is hereby incorporated by reference, discloses a method of optimizing the tooth orientation on a cone. It is herein disclosed that within an optimal range of orientations, the tooth orientation within a single row or between the heel rows of two or more cones can be varied to lessen the propensity for tracking. It is understood in this context that references to "tooth" or "teeth" include both milled teeth and elongated inserts, and that the invention is not specifically limited to the use of steel teeth.

In one class of embodiments, the orientations of the teeth are varied between the heel row of one cone and the heel row of another cone. Since the heel rows of all three cones normally follow the same path, reduction in tracking propensity is particularly useful here.

In another class of embodiments, the orientations of the teeth are varied within a single row of a cone. This helps to avoid same-row tracking forces: tracking is not only caused by the impressions of a preceding cone. The inner rows of teeth are usually spaced so that no two rows follow the same path on the cutting face; but a single row of teeth, on a single cone, will still encounter the impressions left by its own previous path. Since a full circle of a row's path will not necessarily be an exact multiple of the spacing of impressions on the cutting face, the misalignment of teeth to previous impressions may indeed contribute a lateral force component. Here too a difference in orientation between tooth and impression helps to reduce this lateral force component. The different tooth orientations can be grouped in blocks in a given row, such as a block of teeth with orientation A which extends over half the row circumference and a block of teeth with orientation B which extends over the other half; or blocks ABAB, where each block extends over 90 degrees; or blocks ABC; or the blocks can have unequal numbers of teeth.

The disclosed innovations, in various embodiments, provide one or more of at least the following advantages:

- reduces propensity to track rows on different cones that drill the same circumferential path of the hole bottom;
- reduces propensity to track the other teeth on the same row of a cone;
- minimizes vibration during drilling;
- increases lifetime of drill bit and drill string components;
- reduces drilling cost-per-foot.

BRIEF DESCRIPTION OF THE DRAWING

The disclosed inventions will be described with reference to the accompanying drawings, which show important sample embodiments of the invention and which are incorporated in the specification hereof by reference, wherein:

FIGS. 1A to 1C are schematic side views of first, second, and third cones of a drill bit showing only their heel rows, which are oriented in accordance with a preferred embodiment of the present invention.

FIG. 1D is a schematic side view of a drill bit cone showing only an inner row of teeth oriented in accordance with a preferred embodiment of the present invention.

FIG. 2 is a view from the bottom of a conventional drill bit having three cones with chisel inserts for teeth.

FIG. 3 is a side view of a conventional roller cone bit.

FIG. 4 is a side view of a conventional drag bit.

FIG. 5 is a side view schematic of a drilling rig.

FIGS. 6A–C are examples respectively of the impression distribution on the hole bottom of A) a first cone on a drill bit after one bit revolution, B) a first cone on a drill bit after two bit revolutions, showing how tracking can occur, and C) all teeth of a bit after one bit revolution.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The numerous innovative teachings of the present application will be described with particular reference to the presently preferred embodiment (by way of example, and not of limitation).

Co-pending application Ser. No. 09/387,304, filed Aug. 31, 1999, now U.S. Pat. No. 6,095,262 discloses a method of determining the trajectory of each tooth as it traverses the hole bottom, then using this information to optimize the orientation of the teeth accordingly. In all examples discussing the orientation of the teeth, it is understood that all angles will be chosen to be within an optimal range, as determined by this or a similar method, so that drilling efficiency is not adversely affected.

FIG. 1A is schematic side view of first cone 102 of a three-cone bit in accordance with a preferred embodiment of the present disclosure. This diagram shows only one tooth in the outermost or gage row, however it will be understood that the cone has multiple rows of teeth, with multiple teeth in the rows. The tooth shown in cone 102 in the outermost row 104 has chisel shaped inserts 106 in which the elongated portion of chisel inserts 106 are orientated at an angle A, here 160 degrees from the center axis of rotation of cone 102

FIG. 1B is schematic side view of a second cone 112 of the same roller cone bit. Cone 112 has an outermost row 114 having chisel shaped inserts 116 in which the elongated portion of the chisel inserts are oriented at an angle B, here 140 degrees from the center axis of rotation of cone 112. Principle to this embodiment is that angle A and angle B are not the same, but both are within the optimal range of angles as determined by the method of application Ser. No. 09/387,304, filed Aug. 31, 1999, U.S. Pat. No. 6,095,262. In this configuration, teeth 106 of first cone 102, and teeth 116 of second cone 112 are thus aligned in different orientations. The difference in orientation causes the generation of dissimilar impressions in the hole bottom pattern by teeth 106 and teeth 116. Tracking by the consecutive engagement of teeth 106, and teeth 116 with the formation is thus prevented.

FIG. 1C is a schematic side view of a cone 122 of the same roller cone bit. Cone 122 has an outermost row 124 having chisel shaped inserts 126 in which the elongated portion of chisel inserts 126 are orientated at an angle C, here 160 degrees from the center axis of rotation of cone 122. Note that angle C is different from both angle A and angle B, but will still be within the optimal range determined for this location.

FIG. 1D is a schematic side view of a cone 132 of a roller cone bit. Cone 132 has an inner row 134 having chisel shaped inserts 136 in which the elongated portion of chisel inserts 136 are orientated at an angle D, here 20 degrees from the center axis of rotation of cone 132. Also in inner row 134, are chisel inserts 138, in which the elongated portion of the chisel inserts is orientated at an angle E, here 40 degrees from the center axis of rotation of cone 132. Principle to this embodiment is that angle D and angle E are not the same, but are within an optimal range. In this configuration, teeth 136 of row 134, and teeth 138 of row 134 are thus aligned in different orientations. The difference in orientation causes the generation of dissimilar impressions on the hole bottom by teeth 136 and teeth 138. Tracking by the consecutive engagement of teeth 136, and teeth 138 with the formation is thus prevented.

Operation of the Invention

In the operation of the preferred embodiment, a roller cone rock bit has a first cone 102 having an outermost row 104 of teeth 106 oriented at an angle A degrees to the center axis of cone 102. The roller cone rock bit has a second cone 112 having an outermost row 114 of teeth 116 oriented at an angle B degrees to the center axis of cone 112. Since angle A does not equal angle B, teeth 106 of first cone 102, and teeth 116 of second cone 112 are thus aligned at different orientations. When operating torque and weight are applied to the rock bit, teeth 106 and teeth 116 will engage the formation of the hole bottom and crush and scrap the formation away. In doing so, each engagement of teeth 106 and teeth 116 results in the creation of a crater in the hole bottom. The shape and size of the craters depends in a large part on the precise orientations of teeth 106 and teeth 116 in relation to the center axes of respective first cone 102 and second cone 112. The difference in orientation causes the generation of dissimilar impressions on the hole bottom by teeth 106 and teeth 116. Since outermost rows 104 and 114 of cones 102 and 112 follow each other in substantially the same path around the well bottom as the rock bit rotates, tracking by the consecutive engagement of teeth 106 and 116 with the formation is prevented.

In accordance with another preferred embodiment of the present invention, a roller cone rock bit has a cone 122. Cone 122 has an inner row 124, in which is located tooth 126. Tooth 126 is oriented at an angle A degrees to the center axis of cone 122. Also located in inner row 124 is tooth 128. Tooth 128 is oriented at an angle B degrees to the center axis of cone 122. Since angle A and angle B are not equal in this configuration, tooth 126 and tooth 128 are aligned at different orientations. The difference in orientation causes the generation of dissimilar impressions on the hole bottom by tooth 126 and tooth 128. Since inner row 124 of cone 122 drills a concentric ring in the hole bottom without substantial overlap by the teeth of other cones, tracking by the consecutive engagement of tooth 126, and tooth 128 with the formation is prevented.

Definitions:

Following are short definitions of the usual meanings of some of the technical terms which are used in the present application. (However, those of ordinary skill will recognize whether the context requires a different meaning.) Additional definitions can be found in the standard technical dictionaries and journals.

The "cones" in a roller cone bit need not be perfectly conical (nor perfectly frustroconical), but often have a slightly swollen axial profile.

Offset angle: the angular difference by which the axes of the cones do not intersect the centerline of the borehole.

Journal angle: the angle by which the centerline of the bearings intersects the horizontal plane of the bottom of the hole.

Gage row or heel row: the outermost row of teeth on a roller cone, i.e. the teeth which come nearest to the outermost diameter of the hole bottom.

According to a disclosed class of innovative embodiments, there is provided: A roller cone bit comprising: a plurality of non-axially-symmetric teeth mounted on rotatable elements, wherein ones of said teeth which follow the same path on a cutting face have different axial orientations; whereby the likelihood of tracking is reduced.

According to another disclosed class of innovative embodiments, there is provided: A bit for downhole rotary drilling, comprising: a rotatable element which includes a row of teeth; wherein a first one of said teeth has a first orientation and a second one of said teeth has a second orientation which differs from said first orientation.

According to another disclosed class of innovative embodiments, there is provided: A bit for downhole rotary drilling, comprising: a body having an attachment portion capable of being attached to a drill string; cutting elements rotatably attached to said body, each said element including multiple rows of teeth; wherein at least one of said rows on at least one said cutting element includes first and second teeth which are non-axisymmetric; wherein said first tooth has a first orientation and said second tooth has a second orientation which differs from said first orientation.

According to another disclosed class of innovative embodiments, there is provided: A drill bit, comprising: a plurality of rotatable elements mounted to roll along a cutting face when said drill bit is rotated under load, each said rotatable element having a heel row and inner rows of teeth thereon; wherein ones of said teeth in the heel row of a first one of said plurality of rotatable elements have crest orientations which are different from ones of said teeth in the heel row of a second one of said plurality of rotatable elements.

According to another disclosed class of innovative embodiments, there is provided: A roller cone bit comprising: a plurality of cones, each cone having a circumferential outermost row containing a plurality of teeth; a first cone, having in its outermost row a first plurality of teeth having a first axial orientation; and, a second cone, having in its outermost row, a second plurality of teeth having a second axial orientation which is not the same as said first axial orientation.

According to another disclosed class of innovative embodiments, there is provided: A rotary drilling system, comprising: a drill string which is connected to a bit; and a rotary drive which rotates at least part of said drill string together with said bit; wherein said bit comprises a plurality of rotatable elements mounted to roll along a cutting face when said drill bit is rotated under load, each said rotatable element having teeth thereon; wherein ones of said teeth which follow the same path on a cutting face have different axial orientations.

According to another disclosed class of innovative embodiments, there is provided: A rotary drilling system, comprising: a drill string which is connected to a bit; and a rotary drive which rotates at least part of said drill string together with said bit; wherein said bit comprises a plurality of rotatable elements mounted to roll along a cutting face when said drill bit is rotated under load, each said rotatable element having an outer row and inner rows of teeth thereon; wherein a first plurality of said teeth have crest orientations which are different from the crest orientations of a second plurality of teeth in said bit.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a bit for rotary drilling, comprising the actions of: determining an optimal range of orientations for teeth for each row of each cone; providing a variation in the orientations of ones of said teeth which follow the same path on a cutting face; whereby tracking is reduced.

According to another disclosed class of innovative embodiments, there is provided: A method for rotary drilling, comprising the actions of: (a.) installing, on the drill string, a rotary drill bit whose tooth orientation has been optimized to provide a variation in the orientations of ones of said teeth which follow the same path on a cutting face; (b.) rotating at least a portion of said drill string which includes said drill bit; whereby tracking is reduced.

Modifications and Variations

As will be recognized by those skilled in the art, the innovative concepts described in the present application can be modified and varied over a tremendous range of applications, and accordingly the scope of patented subject matter is not limited by any of the specific exemplary teachings given.

Additional general background, which helps to show the knowledge of those skilled in the art regarding implementations and the predictability of variations, may be found in the following publications, all of which are hereby incorporated by reference: APPLIED DRILLING ENGINEERING, Adam T. Bourgoyne Jr. et al., Society of Petroleum Engineers Textbook series (1991), OIL AND GAS FIELD DEVELOPMENT TECHNIQUES: DRILLING, J.-P. Nguyen (translation 1996, from French original 1993), MAKING HOLE (1983) and DRILLING MUD (1984), both part of the Rotary Drilling Series, edited by Charles Kirkley.

None of the description in the present application should be read as implying that any particular element, step, or function is an essential element which must be included in the claim scope: THE SCOPE OF PATENTED SUBJECT MATTER IS DEFINED ONLY BY THE ALLOWED CLAIMS. Moreover, none of these claims are intended to invoke paragraph six of 35 USC section 112 unless the exact words "means for" are followed by a participle.

What is claimed is:

1. A roller cone bit comprising:

a plurality of non-axially-symmetric teeth mounted on rotatable elements, wherein ones of said teeth which follow the same path on a cutting face have different axial orientations;

wherein a first plurality of said ones of said teeth are contiguous and all have a first orientation, and a second plurality of said ones of teeth are contiguous and all have a second orientation;

whereby the likelihood of tracking is reduced.

2. A bit for downhole rotary drilling, comprising:

a rotatable element which includes a row of teeth;

wherein a first plurality of said teeth are contiguous and all have a first orientation, and a second plurality of said teeth are contiguous and all have a second orientation which differs from said first orientation.

3. A bit for downhole rotary drilling, comprising:

a body having an attachment portion capable of being attached to a drill string;

cutting elements rotatably attached to said body, each said element including multiple rows of teeth;

wherein at least one of said rows on at least one said cutting element includes teeth which are non-axisymmetric;

wherein a first plurality of said non-axisymmetric teeth are contiguous and all have a first orientation, and a second plurality of said non-axisymmetric teeth are contiguous and all have a second orientation which differs from said first orientation.

4. The bit of claim 3, wherein said bit is a tricone bit.

5. A drill bit, comprising:

a plurality of rotatable elements mounted to roll along a cutting face when said drill bit is rotated under load, each said rotatable element having a heel row and inner rows of teeth thereon;

wherein multiple contiguous ones of said teeth in the heel row of a first one of said plurality of rotatable elements have a common crest orientation which is different from ones of said teeth in the heel row of a second one of said plurality of rotatable elements.

6. A roller cone bit comprising:

a plurality of cones, each cone having a circumferential outermost row containing a plurality of teeth;

a first cone, having in its outermost row a first contiguous plurality of teeth having a first axial orientation; and a second cone, having in its outermost row a second contiguous plurality of teeth having a second axial orientation which is not the same as said first axial orientation.

7. The roller cone bit of claim 6, further comprising a third cone, having in its outermost row, a third plurality of teeth having a third axial orientation which is not the same as said first or said second axial orientation.

8. A rotary drilling system, comprising:

a drill string which is connected to a bit; and

a rotary drive which rotates at least part of said drill string together with said bit;

wherein said bit comprises

a plurality of rotatable elements mounted to roll along a cutting face when said drill bit is rotated under load, each said rotatable element having teeth thereon;

wherein ones of said teeth which follow the same path on a cutting face have different axial orientations;

wherein a first plurality of said ones of said teeth are contiguous and have a first orientation, and a second plurality of said ones of said teeth are contiguous and have a second orientation which is different from said first orientation.

9. A method of designing a bit for rotary drilling, comprising the actions of:

determining an optimal range of orientations for teeth for each row of each cone;

providing a variation in the orientations of ones of said teeth which follow the same path on a cutting face;

wherein a first contiguous plurality of said ones of said teeth have a first orientation at a first end of said optimal range of orientations, and a second contiguous plurality of said ones of said teeth have a second orientation at an opposite end of said optimal range;

whereby tracking is reduced.

10. A method for rotary drilling, comprising the actions of:

(a) installing, on the drill string, a rotary drill bit whose tooth orientation has been optimized to provide a difference in the orientations of a first contiguous plurality and a second contiguous plurality of said teeth which follow the same path on a cutting face;

(b) rotating at least a portion of said drill string which includes said drill bit;

whereby tracking is reduced.

11. The method of claim 10, further comprising pumping mud down said drill string to exit said rotary drill bit.

* * * * *

US006412577B1

(12) **United States Patent**
Chen

(10) **Patent No.: US 6,412,577 B1**
(45) **Date of Patent: Jul. 2, 2002**

(54) **ROLLER-CONE BITS, SYSTEMS, DRILLING METHODS, AND DESIGN METHODS WITH OPTIMIZATION OF TOOTH ORIENTATION**

(75) Inventor: **Shilin Chen**, Dallas, TX (US)

(73) Assignee: **Halliburton Energy Services Inc.**, Carrollton, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/629,344**

(22) Filed: **Aug. 1, 2000**

Related U.S. Application Data

(63) Continuation of application No. 09/387,304, filed on Aug. 31, 1999, now Pat. No. 6,095,262.
(60) Provisional application No. 60/098,442, filed on Aug. 31, 1998.

(51) **Int. Cl.**[7] **E21B 10/16**
(52) **U.S. Cl.** 175/57; 76/108.2; 175/374
(58) **Field of Search** 175/57, 374, 376, 175/378, 331; 76/108.2, 108.4

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,187,922 A * 2/1980 Phelps 175/374
4,393,948 A * 7/1983 Fernandez 175/374
4,427,081 A * 1/1984 Crawford 175/376
4,815,342 A * 3/1989 Brett et al. 76/108.2
5,197,555 A * 3/1993 Estes 175/431
5,224,560 A * 7/1993 Fernandez 175/374
5,372,210 A * 12/1994 Harrell 175/431
5,415,030 A * 5/1995 Jogi et al. 73/152.03
5,704,436 A * 1/1998 Smith et al. 175/27
5,730,234 A * 3/1998 Putot 175/30
5,767,399 A * 6/1998 Smith et al. 73/152.11
5,794,720 A * 8/1998 Smith et al. 175/40
6,095,262 A * 8/2000 Chen 175/57
6,213,225 B1 * 4/2001 Chen 175/57

FOREIGN PATENT DOCUMENTS

GB 2241266A * 8/1991

* cited by examiner

Primary Examiner—Hoang Dang
(74) *Attorney, Agent, or Firm*—Robert Groover

(57) **ABSTRACT**

A novel and improved roller cone drill bit and method of design are disclosed. A roller cone drill bit for drilling through subterranean formations having an upper connection for attachment to a drill string, and a plurality cutting structures rotatably mounted on arms extending downward from the connection. A number of teeth are located in generally concentric rows on each cutting structure. The actual trajectory by which the teeth engage the formation is mathematically determined. A straight-line trajectory is calculated based on the actual trajectory. The teeth are positioned in the cutting structures such each tooth having a designed engagement surface is oriented perpendicular to the calculated straight-line trajectory.

6 Claims, 21 Drawing Sheets

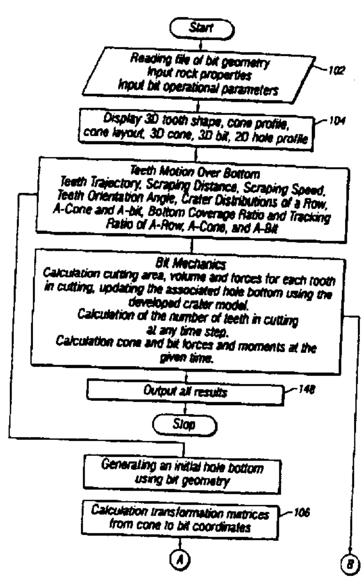


EXHIBIT A4

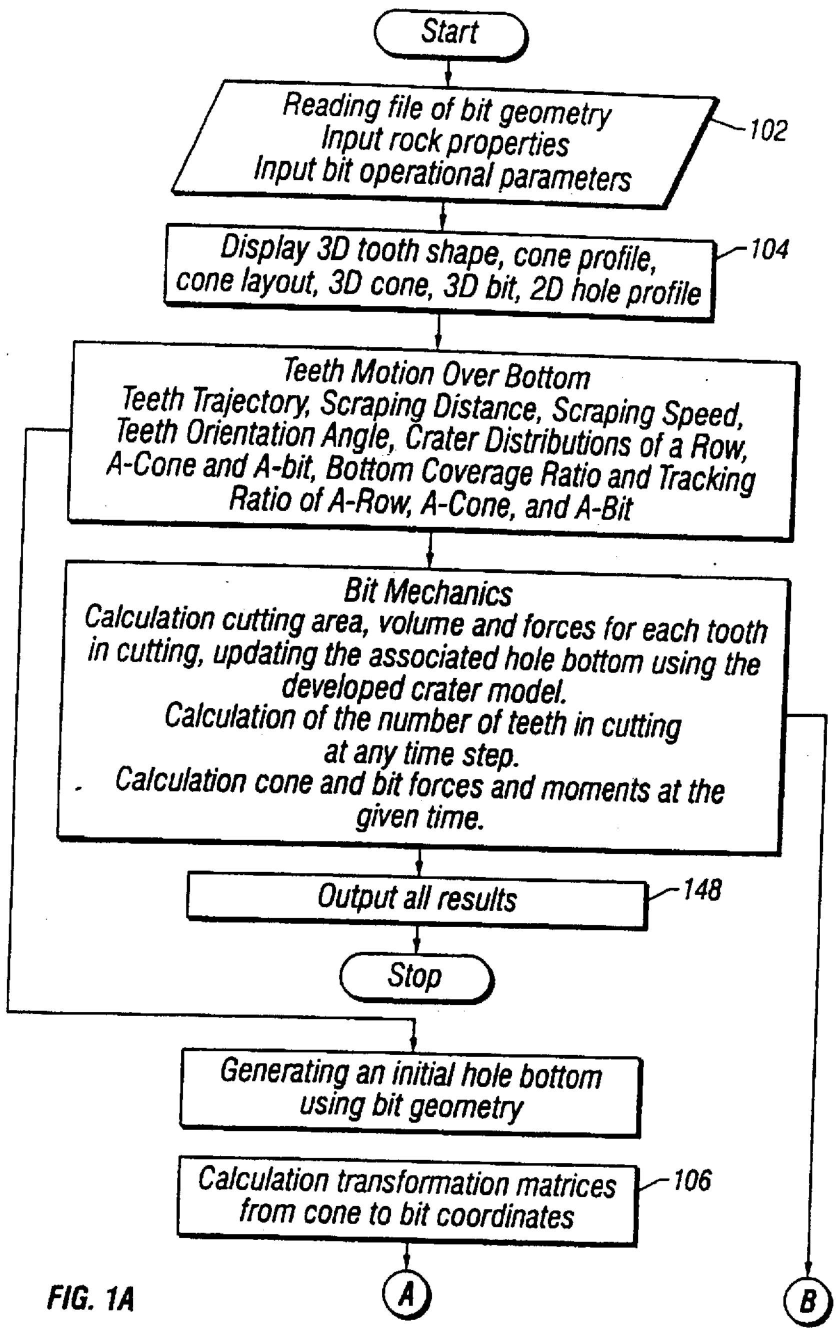

Start
Reading file of bit geometry
Input rock properties
Input bit operational parameters
102
Display 3D tooth shape, cone profile, cone layout, 3D cone, 3D bit, 2D hole profile
104
Teeth Motion Over Bottom
Teeth Trajectory, Scraping Distance, Scraping Speed, Teeth Orientation Angle, Crater Distributions of a Row, A-Cone and A-bit, Bottom Coverage Ratio and Tracking Ratio of A-Row, A-Cone, and A-Bit
Bit Mechanics
Calculation cutting area, volume and forces for each tooth in cutting, updating the associated hole bottom using the developed crater model.
Calculation of the number of teeth in cutting at any time step.
Calculation cone and bit forces and moments at the given time.
Output all results
148
Stop
Generating an initial hole bottom using bit geometry
Calculation transformation matrices from cone to bit coordinates
106
A
B

FIG. 1A

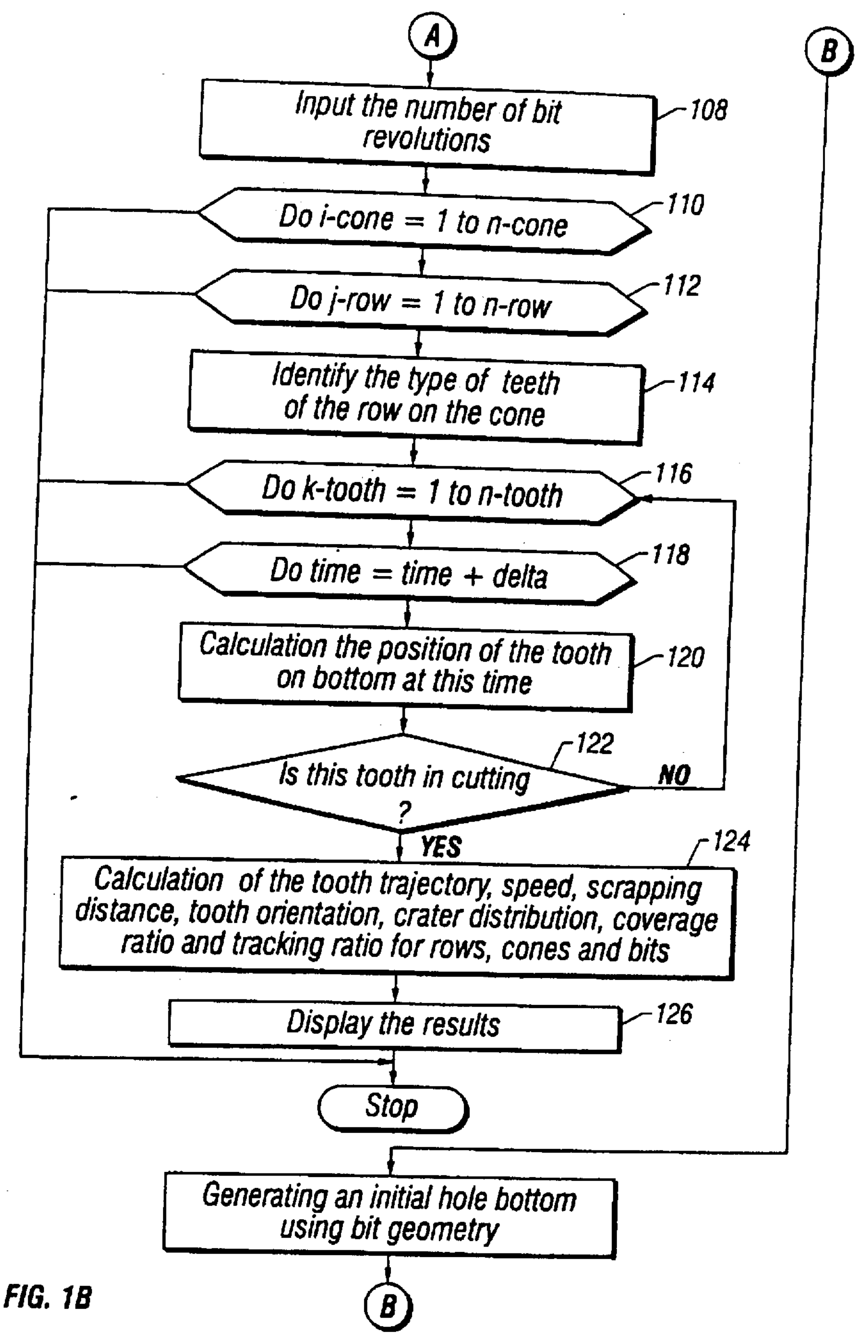

A
B
Input the number of bit revolutions
108
Do i-cone = 1 to n-cone
110
Do j-row = 1 to n-row
112
Identify the type of teeth of the row on the cone
114
Do k-tooth = 1 to n-tooth
116
Do time = time + delta
118
Calculation the position of the tooth on bottom at this time
120
Is this tooth in cutting ?
122
NO
YES
124
Calculation of the tooth trajectory, speed, scrapping distance, tooth orientation, crater distribution, coverage ratio and tracking ratio for rows, cones and bits
Display the results
126
Stop
Generating an initial hole bottom using bit geometry
B

FIG. 1B

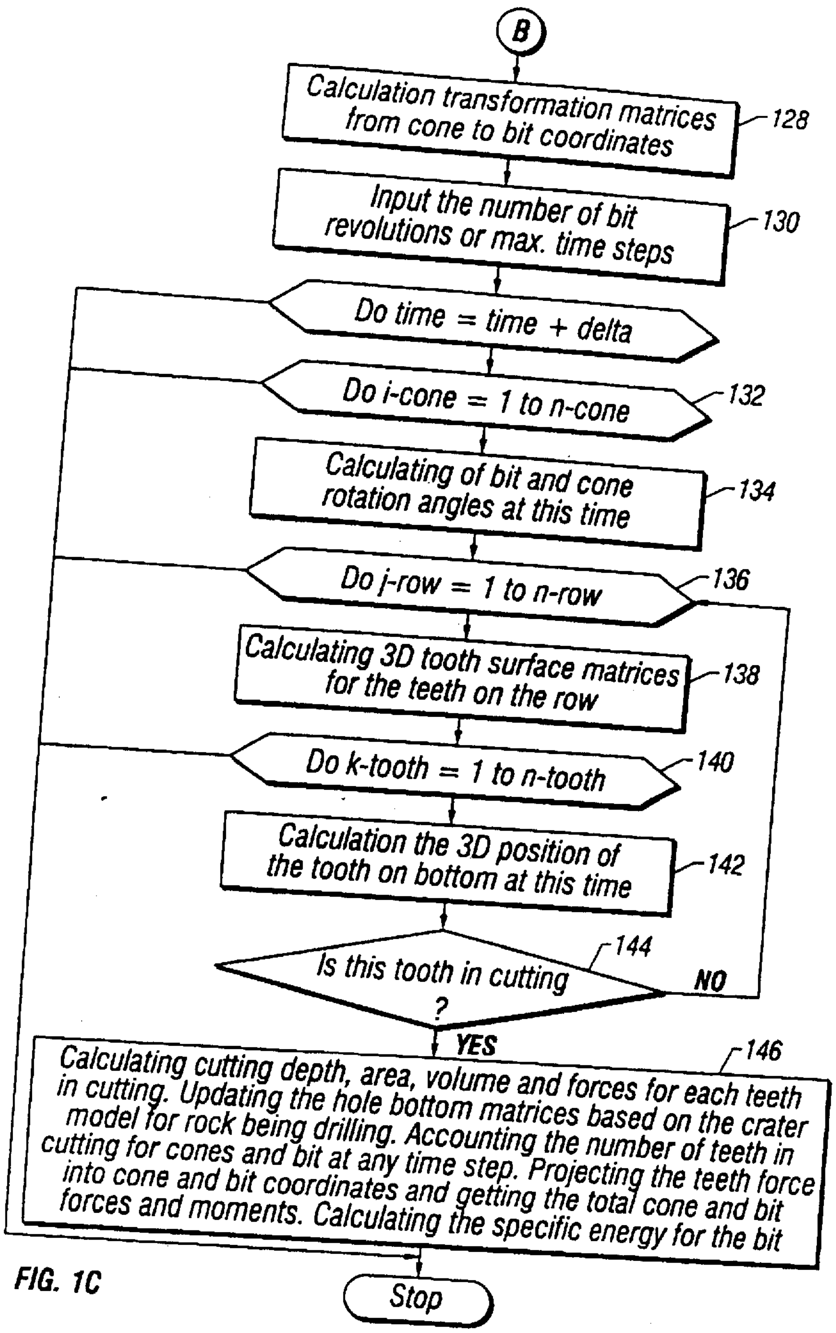

B
Calculation transformation matrices from cone to bit coordinates
128
Input the number of bit revolutions or max. time steps
130
Do time = time + delta
Do i-cone = 1 to n-cone
132
Calculating of bit and cone rotation angles at this time
134
Do j-row = 1 to n-row
136
Calculating 3D tooth surface matrices for the teeth on the row
138
Do k-tooth = 1 to n-tooth
140
Calculation the 3D position of the tooth on bottom at this time
142
Is this tooth in cutting ?
144
NO
YES
146
Calculating cutting depth, area, volume and forces for each teeth in cutting. Updating the hole bottom matrices based on the crater model for rock being drilling. Accounting the number of teeth in cutting for cones and bit at any time step. Projecting the teeth force into cone and bit coordinates and getting the total cone and bit forces and moments. Calculating the specific energy for the bit
Stop

FIG. 1C

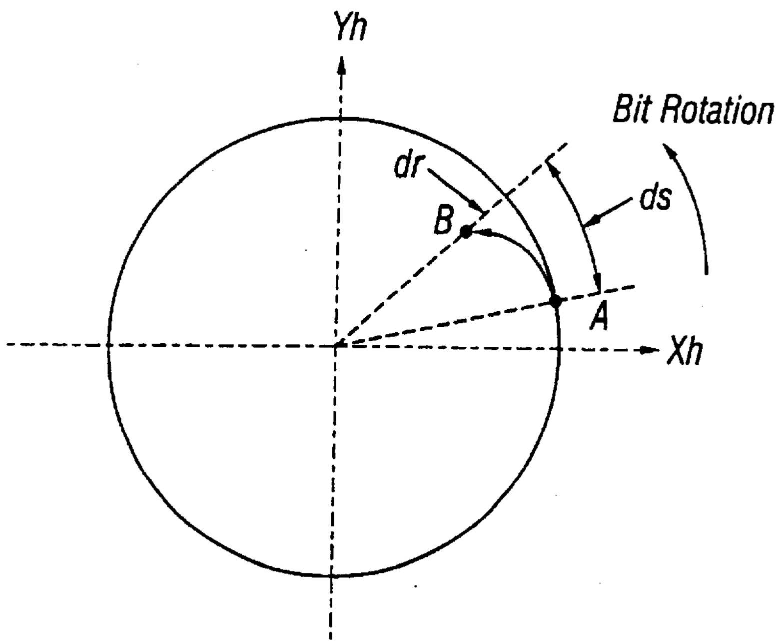


FIG. 2

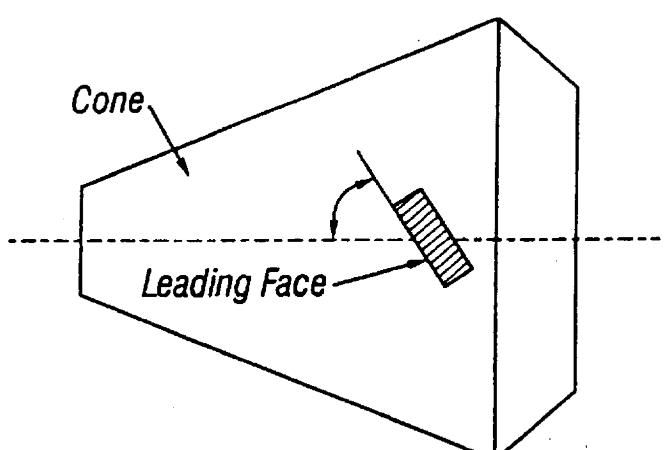


FIG. 5

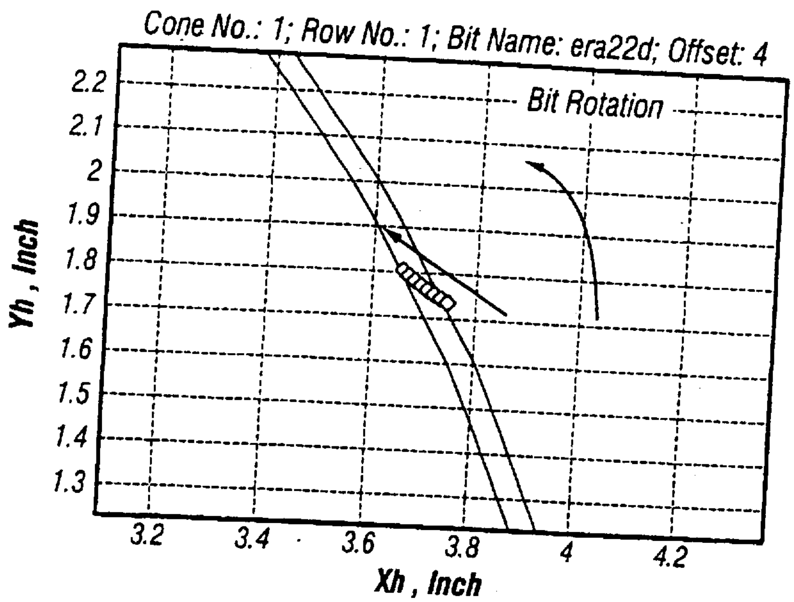

Cone No.: 1; Row No.: 1; Bit Name: era22d; Offset: 4
Bit Rotation
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
Yh , Inch
3.2
3.4
3.6
3.8
4
4.2
Xh , Inch

FIG. 3A

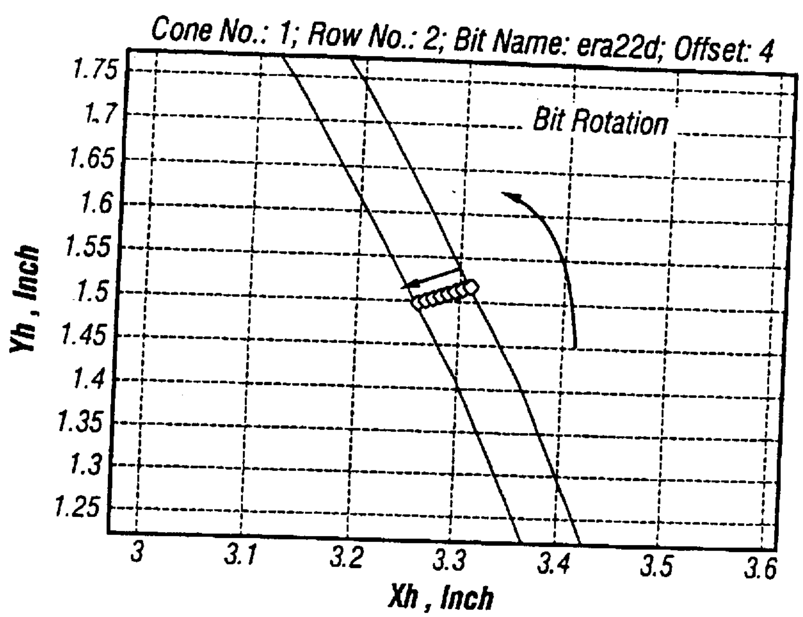

Cone No.: 1; Row No.: 2; Bit Name: era22d; Offset: 4
Bit Rotation
1.75
1.7
1.65
1.6
1.55
1.5
1.45
1.4
1.35
1.3
1.25
Yh , Inch
3
3.1
3.2
3.3
3.4
3.5
3.6
Xh , Inch

FIG. 3B

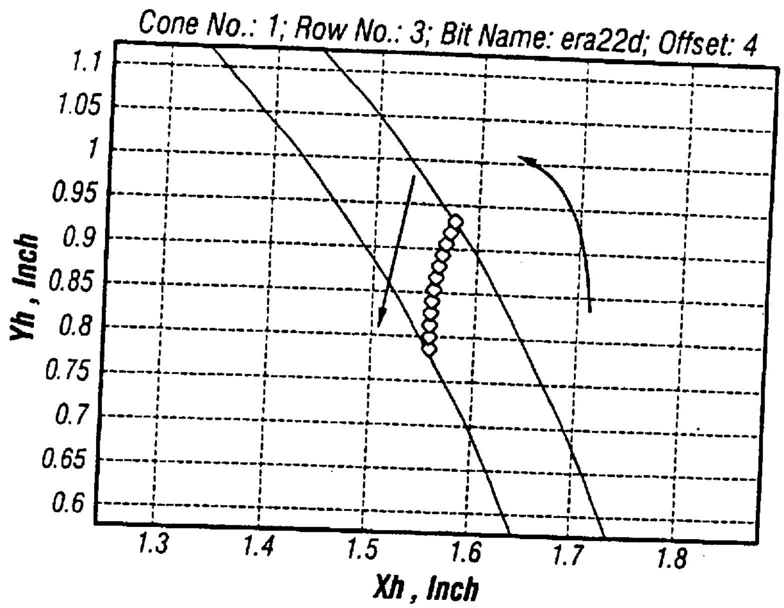

Cone No.: 1; Row No.: 3; Bit Name: era22d; Offset: 4
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Yh , Inch
1.3
1.4
1.5
1.6
1.7
1.8
Xh , Inch

FIG. 3C

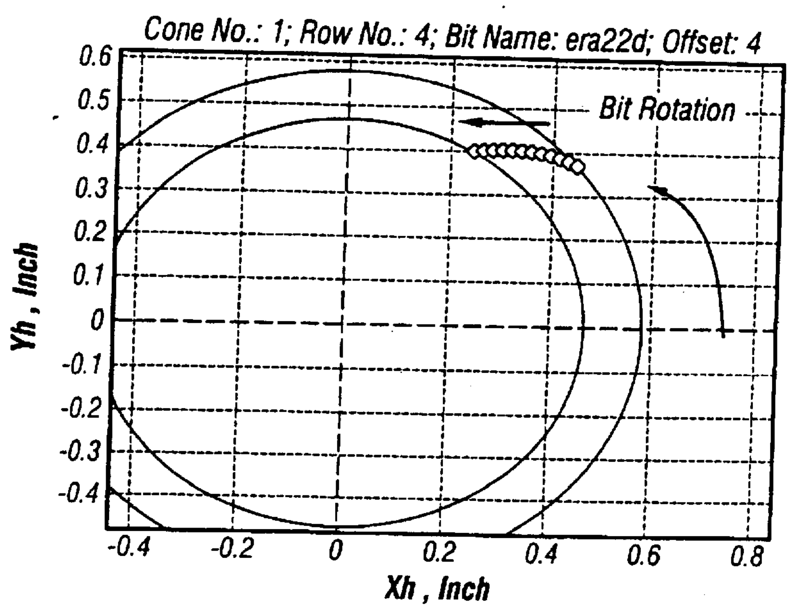

Cone No.: 1; Row No.: 4; Bit Name: era22d; Offset: 4
Bit Rotation
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Yh , Inch
-0.4
-0.2
0
0.2
0.4
0.6
0.8
Xh , Inch

FIG. 3D

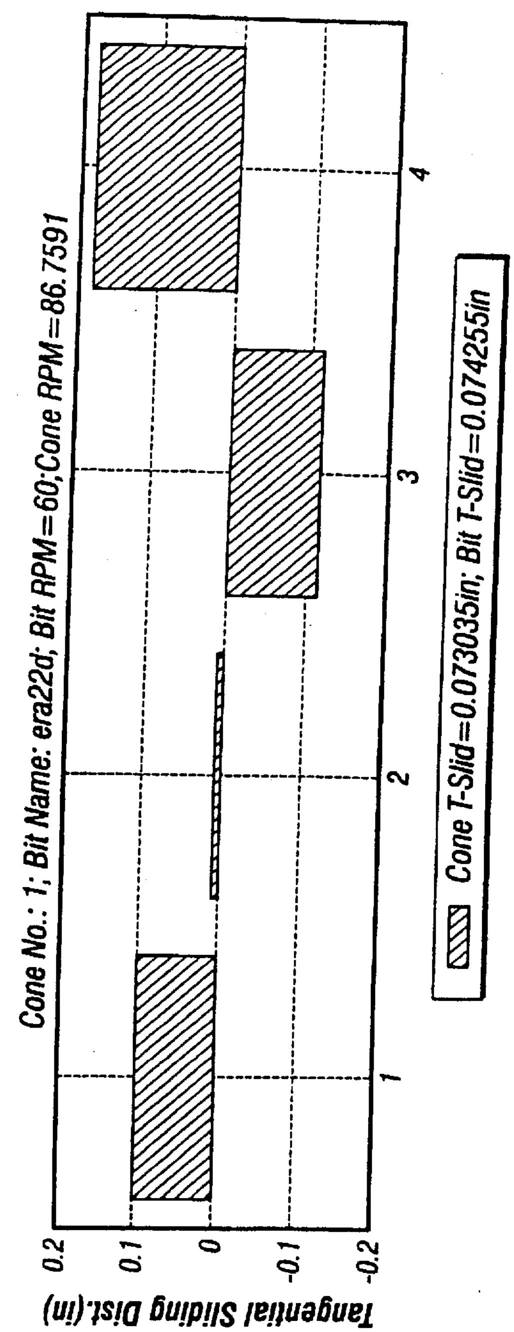

Cone No.: 1; Bit Name: era22d; Bit RPM=60;Cone RPM=86.7591
Tangential Sliding Dist.(in)
0.2
0.1
0
-0.1
-0.2
1
2
3
4
Cone T-Slid=0.073035in; Bit T-Slid=0.074255in

FIG. 4A

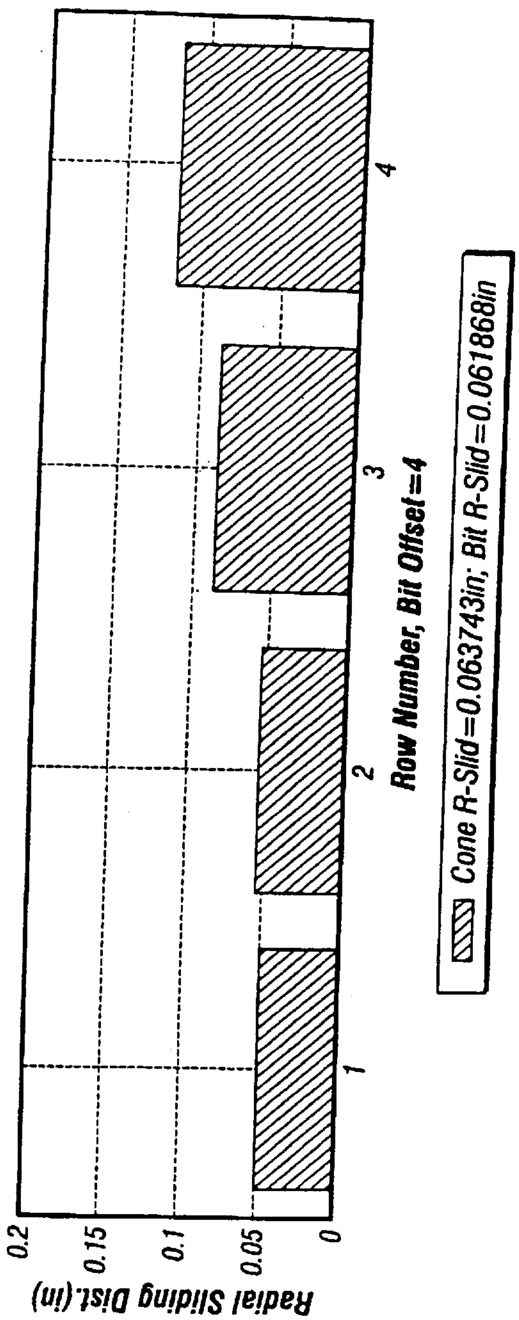

Radial Sliding Dist.(in)
0.2
0.15
0.1
0.05
0
1
2
3
4
Row Number, Bit Offset=4
Cone R-Slid=0.063743in; Bit R-Slid=0.061868in

FIG. 4B

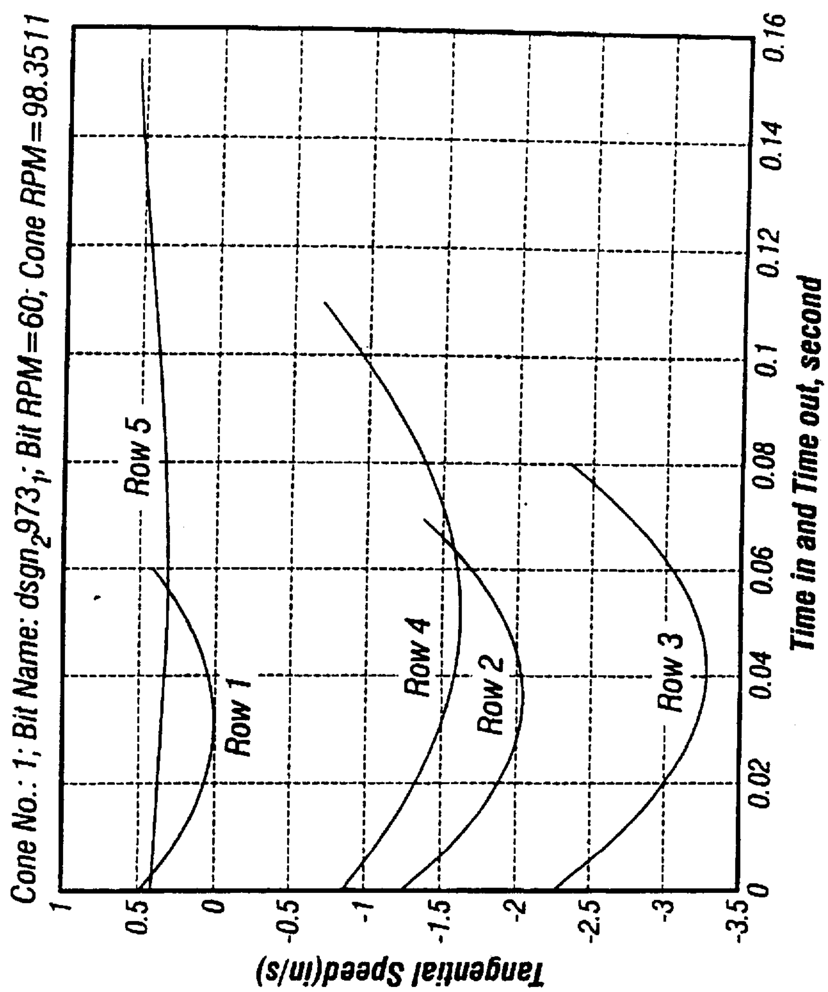

Cone No.: 1; Bit Name: $dsgn_2973_1$; Bit RPM=60; Cone RPM=98.3511
Row 5
Row 1
Row 4
Row 2
Row 3
Tangential Speed(in/s)
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
Time in and Time out, second

FIG. 6

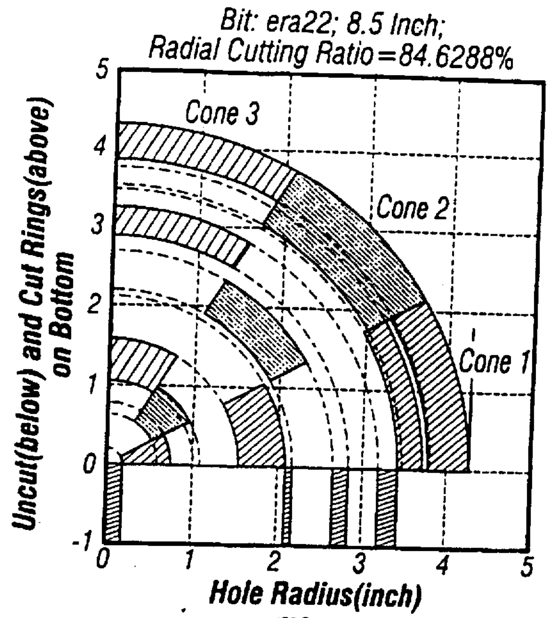

Bit: era22; 8.5 Inch;
Radial Cutting Ratio=84.6288%
Cone 3
Cone 2
Cone 1
Uncut(below) and Cut Rings(above) on Bottom
Hole Radius(inch)
5
4
3
2
1
0
-1
0
1
2
3
4
5

FIG. 7A

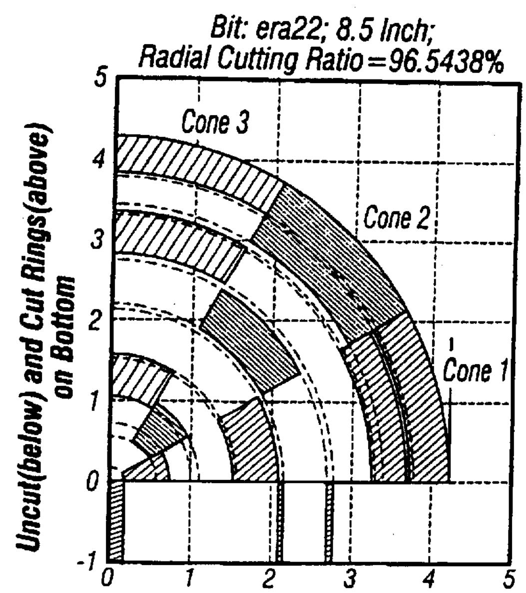
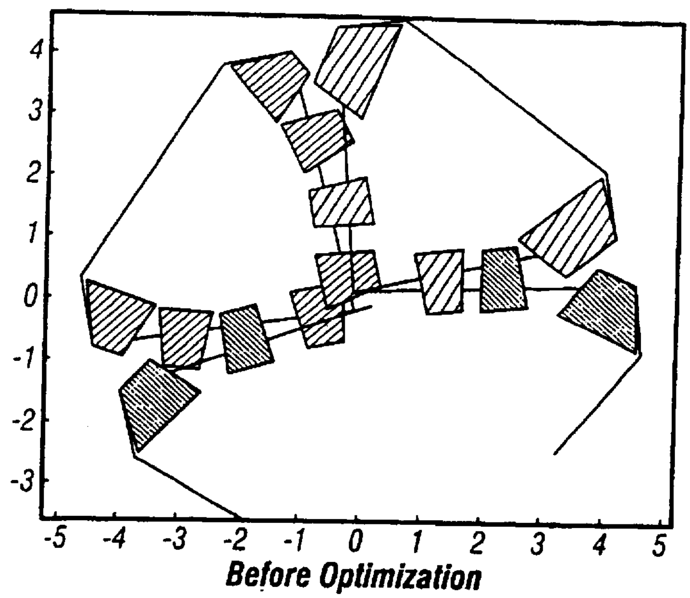
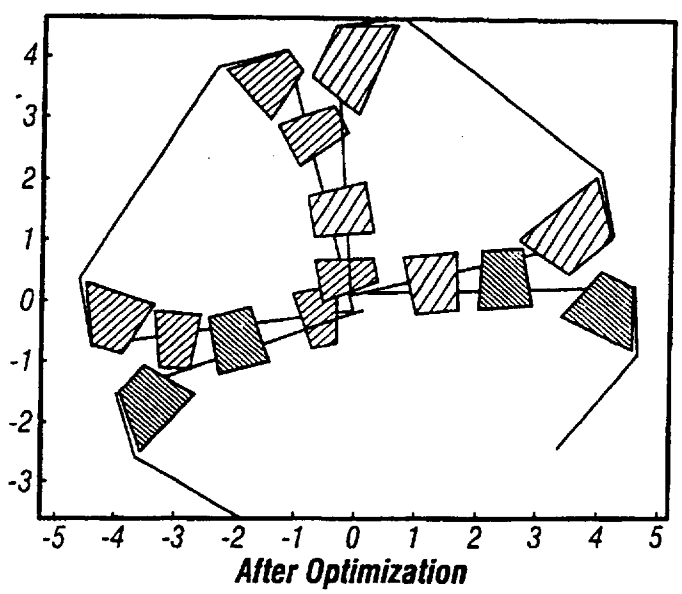

Bit: era22; 8.5 Inch;
Radial Cutting Ratio=96.5438%
Cone 3
Cone 2
Cone 1
Uncut(below) and Cut Rings(above) on Bottom
Hole Radius(inch)
5
4
3
2
1
0
-1
0
1
2
3
4
5

FIG. 7B



4
3
2
1
0
-1
-2
-3
-5 -4 -3 -2 -1 0 1 2 3 4 5
Before Optimization

FIG. 8A



4
3
2
1
0
-1
-2
-3
-5 -4 -3 -2 -1 0 1 2 3 4 5
After Optimization

FIG. 8B

ERA22_V Cone No.1

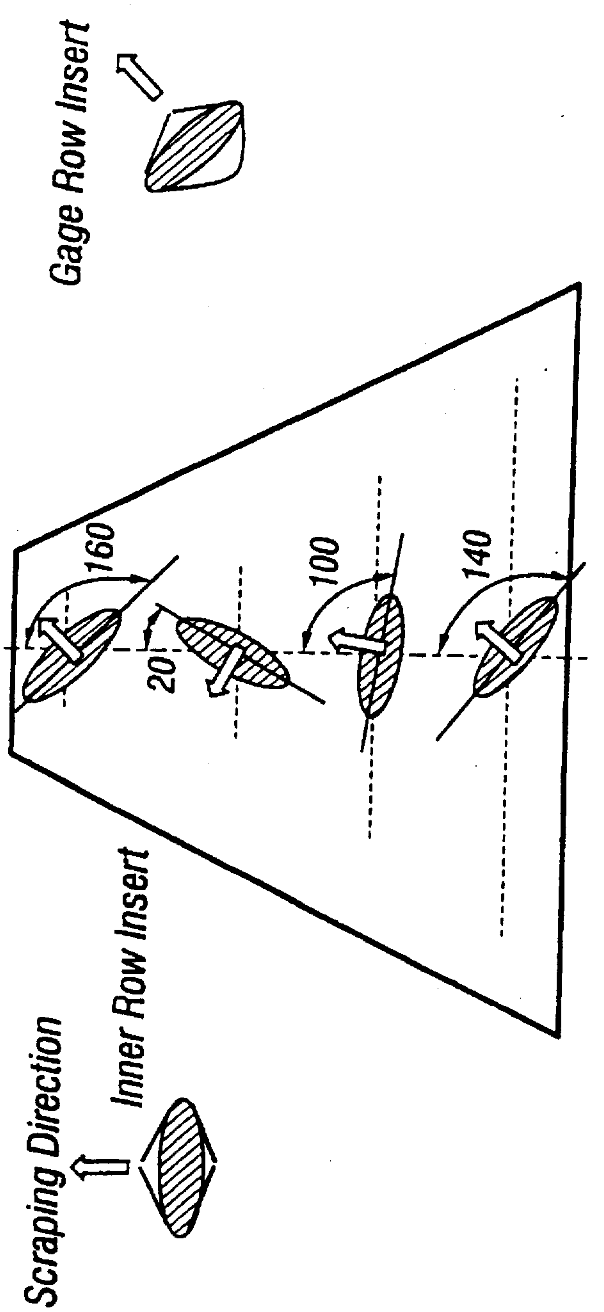


FIG. 9A

ERA22_V Cone No.2

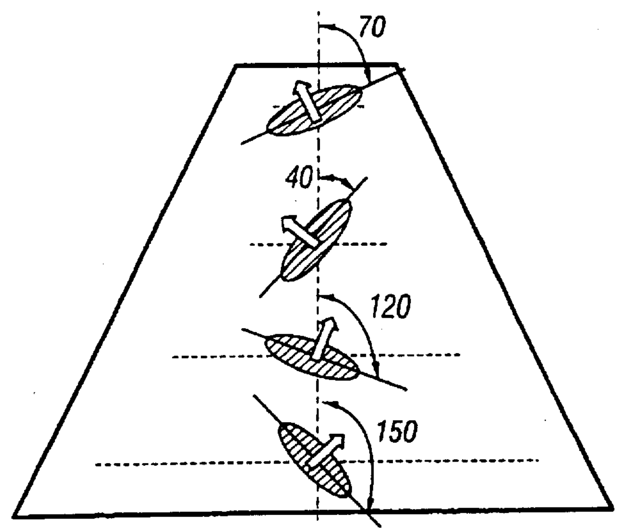


FIG. 9B

ERA22_V Cone No.3

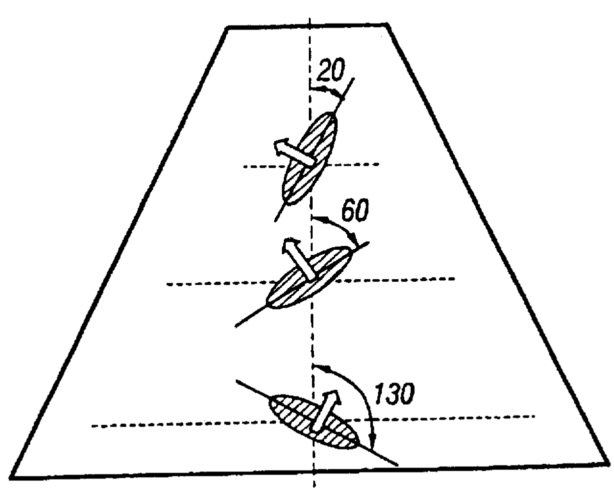


FIG. 9C

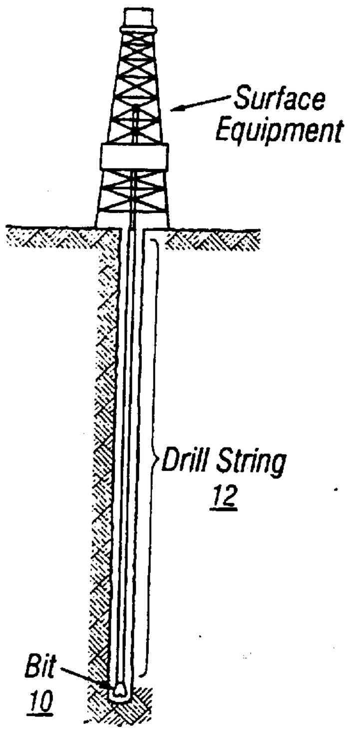


FIG. 10

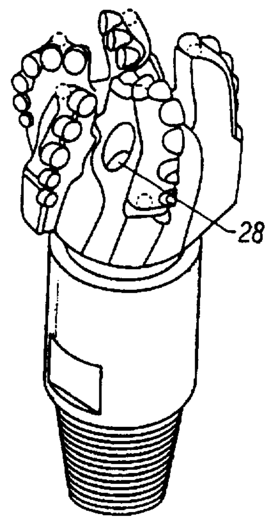


FIG. 11

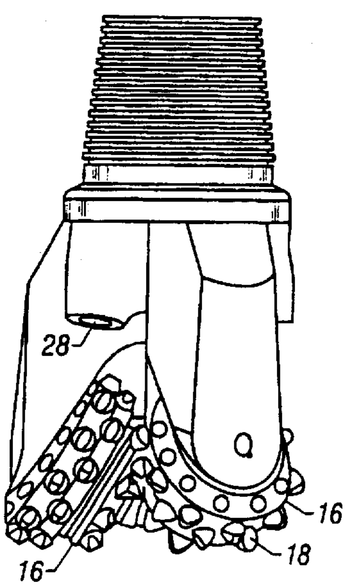


FIG. 12

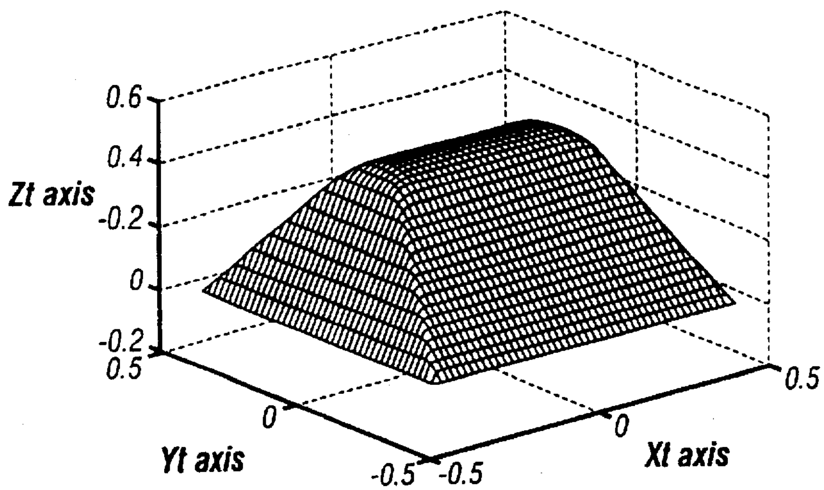

0.6
0.4
Zt axis
-0.2
0
-0.2
0.5
0
Yt axis
-0.5
-0.5
0
Xt axis
0.5

FIG. 13

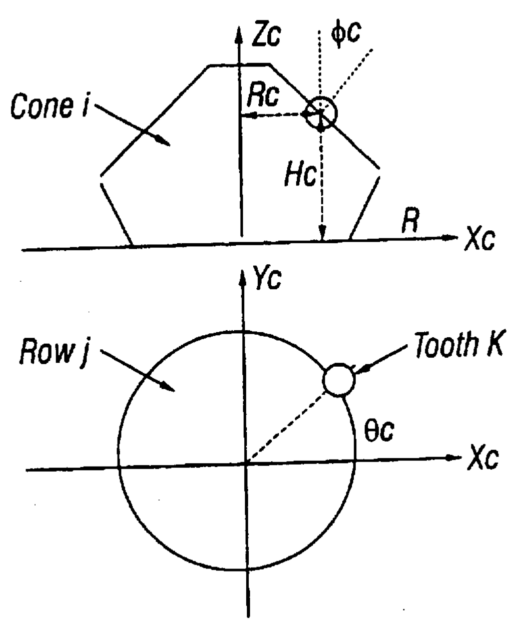

Zc
φc
Cone i
Rc
Hc
R
Xc
Yc
Row j
Tooth K
θc
Xc

FIG. 14

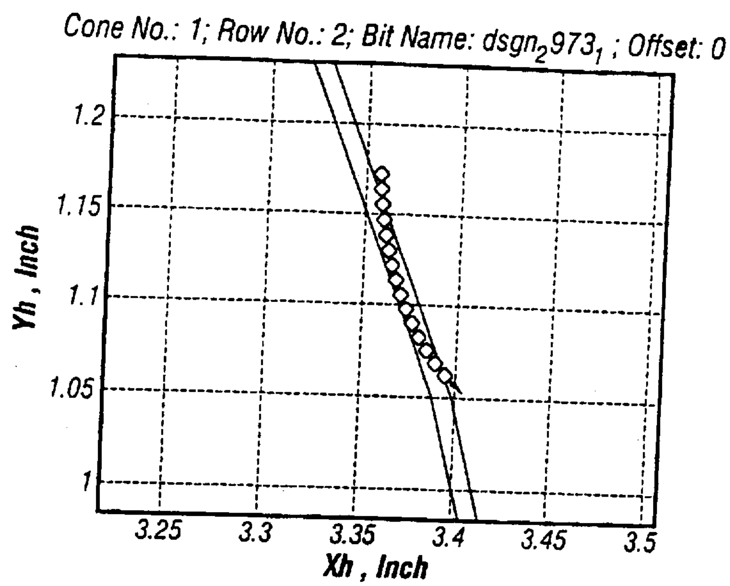


FIG. 15A

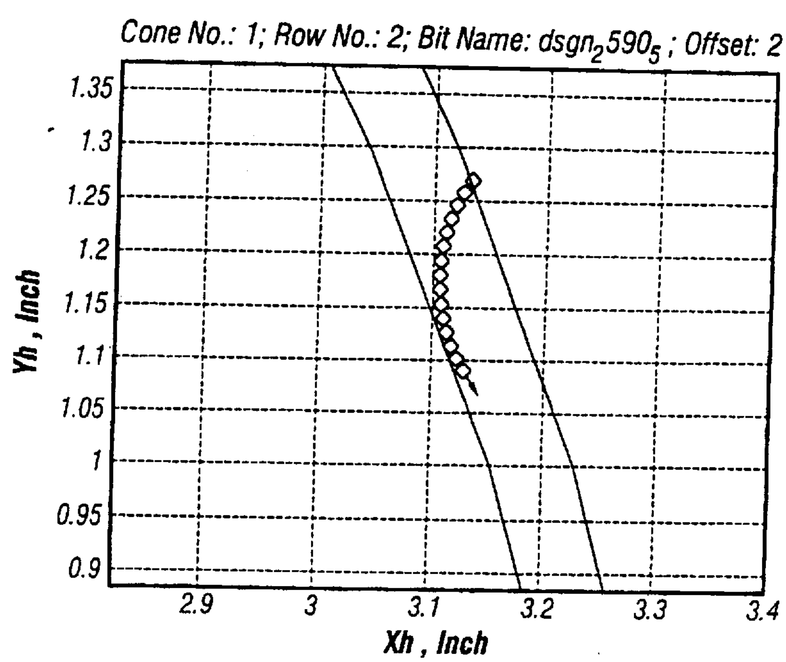


FIG. 15B

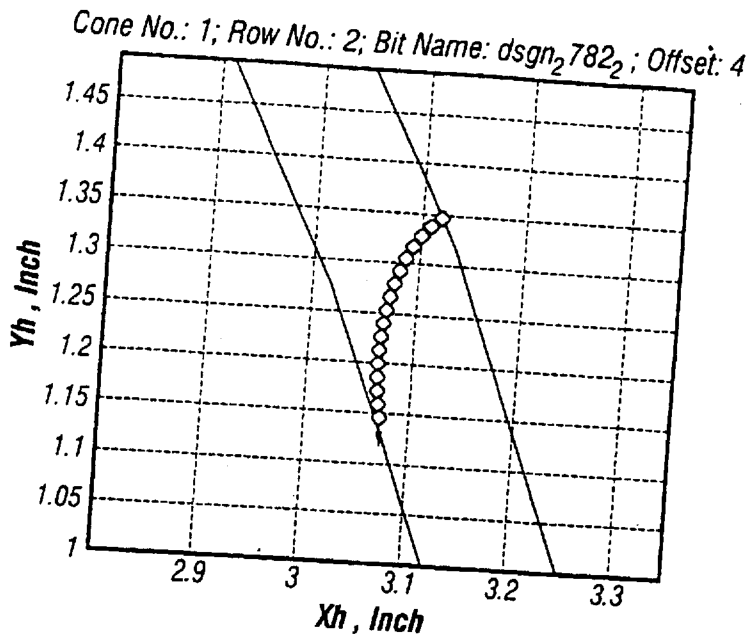


FIG. 15C

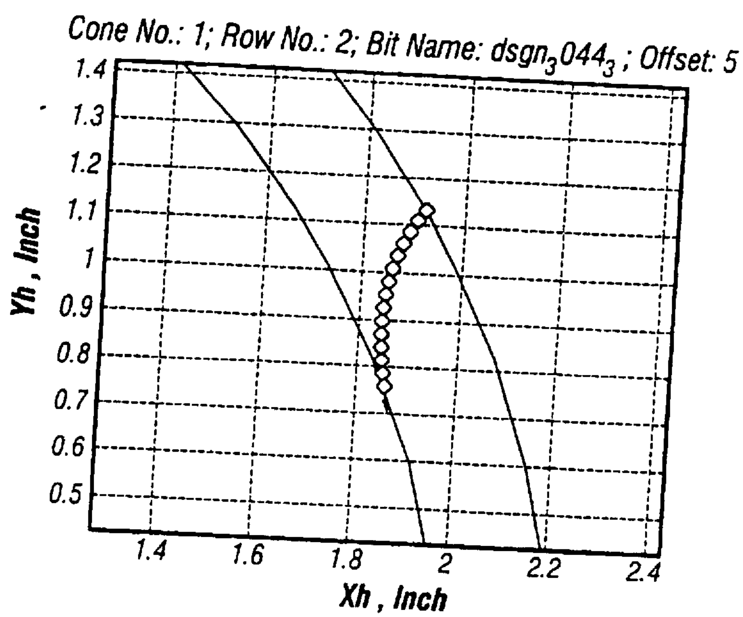


FIG. 15D

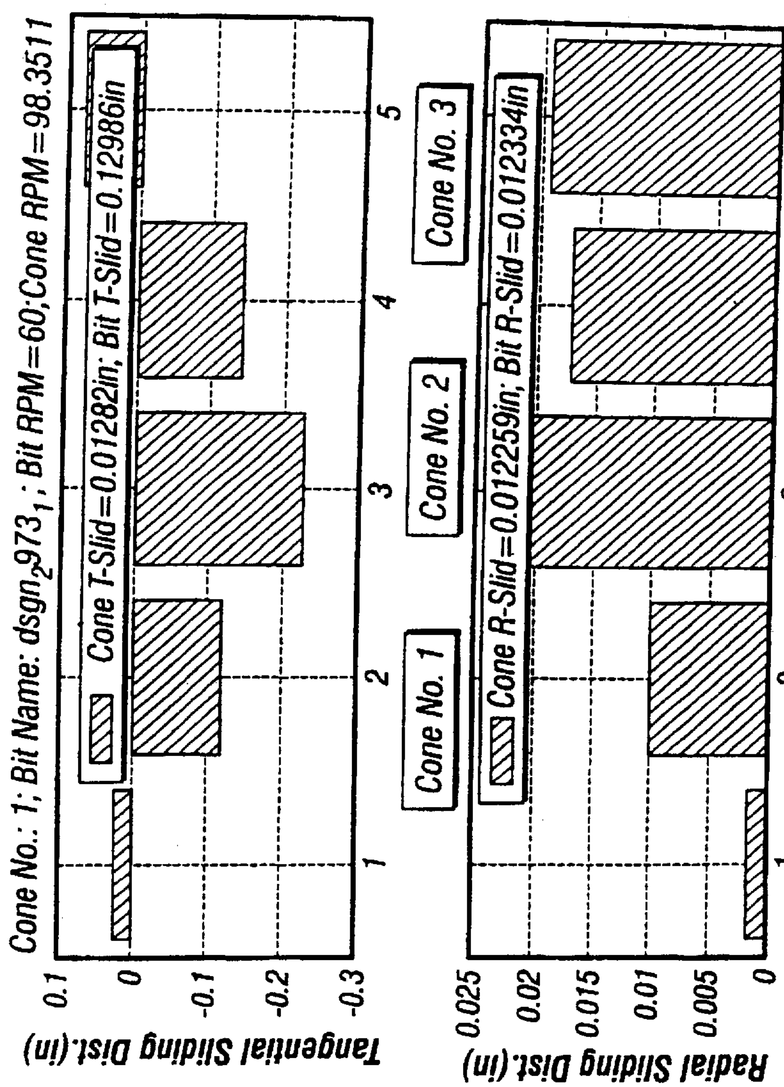

Cone No.: 1; Bit Name: dsgn2973_1; Bit RPM=60;Cone RPM=98.3511
Cone T-Slid=0.01282in; Bit T-Slid=0.12986in
Tangential Sliding Dist.(in)
0.1
0
-0.1
-0.2
-0.3
1
2
3
4
5
Cone No. 1
Cone No. 2
Cone No. 3
Cone R-Slid=0.012259in; Bit R-Slid=0.012334in
Radial Sliding Dist.(in)
0.025
0.02
0.015
0.01
0.005
0

FIG. 16A

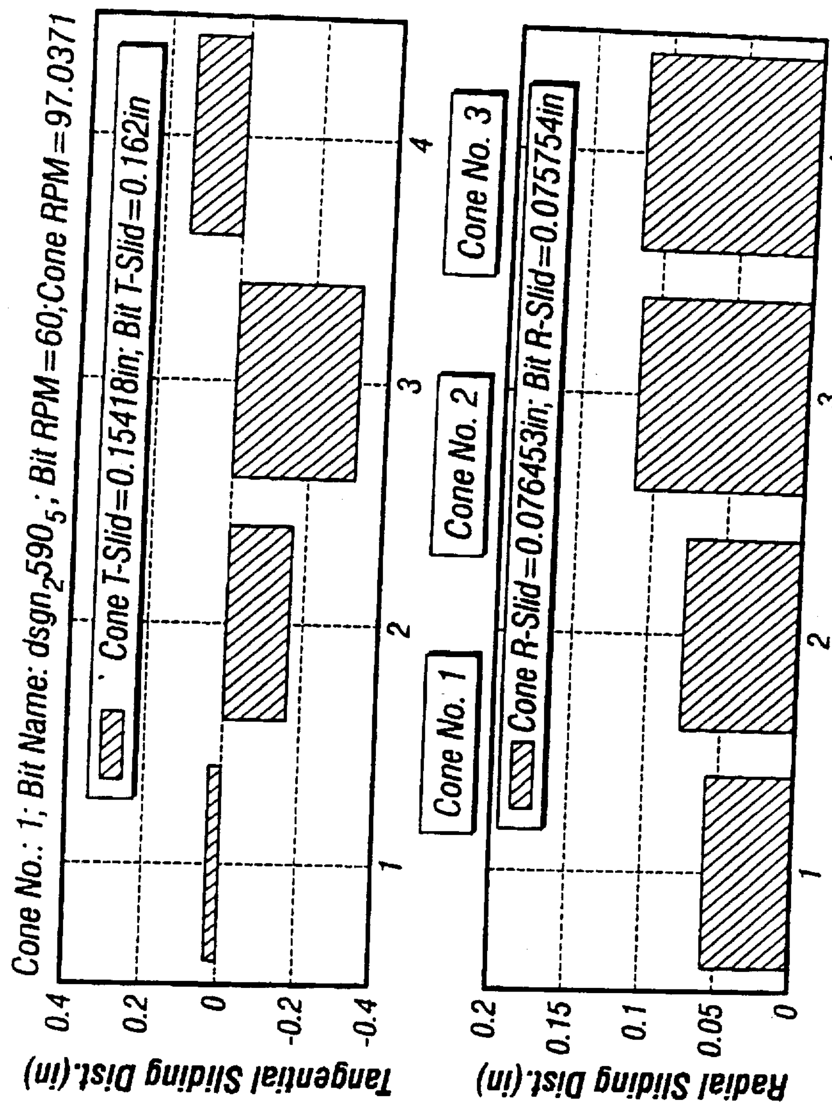

Cone No.: 1; Bit Name: dsgn2590 5; Bit RPM=60;Cone RPM=97.0371
Cone T-Slid=0.15418in; Bit T-Slid=0.162in
Tangential Sliding Dist.(in)
0.4
0.2
0
-0.2
-0.4
1
2
3
4
Cone No. 1
Cone No. 2
Cone No. 3
Cone R-Slid=0.076453in; Bit R-Slid=0.075754in
Radial Sliding Dist.(in)
0.2
0.15
0.1
0.05
0

FIG. 16B

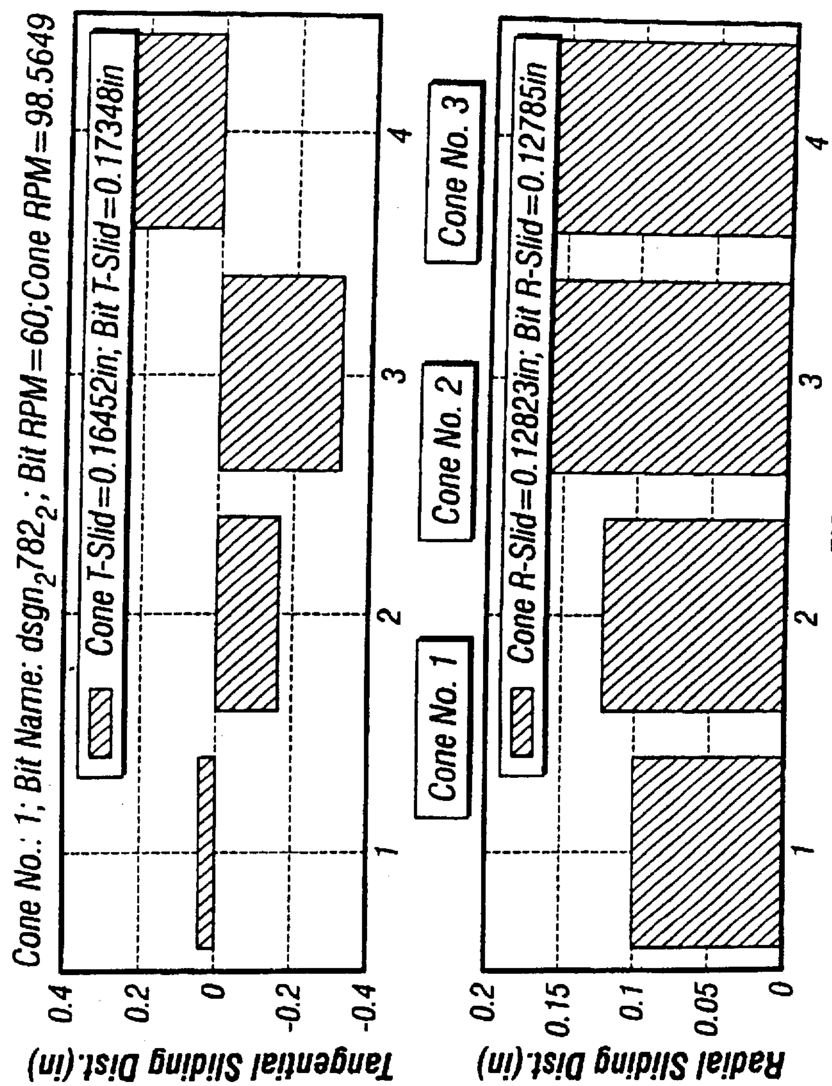

Cone No.: 1; Bit Name: dsgn2782_2; Bit RPM=60;Cone RPM=98.5649
Cone T-Slid=0.16452in; Bit T-Slid=0.17348in
Tangential Sliding Dist.(in)
0.4
0.2
0
-0.2
-0.4
1
2
3
4
Cone No. 1
Cone No. 2
Cone No. 3
Cone R-Slid=0.12823in; Bit R-Slid=0.12785in
Radial Sliding Dist.(in)
0.2
0.15
0.1
0.05
0

FIG. 16C

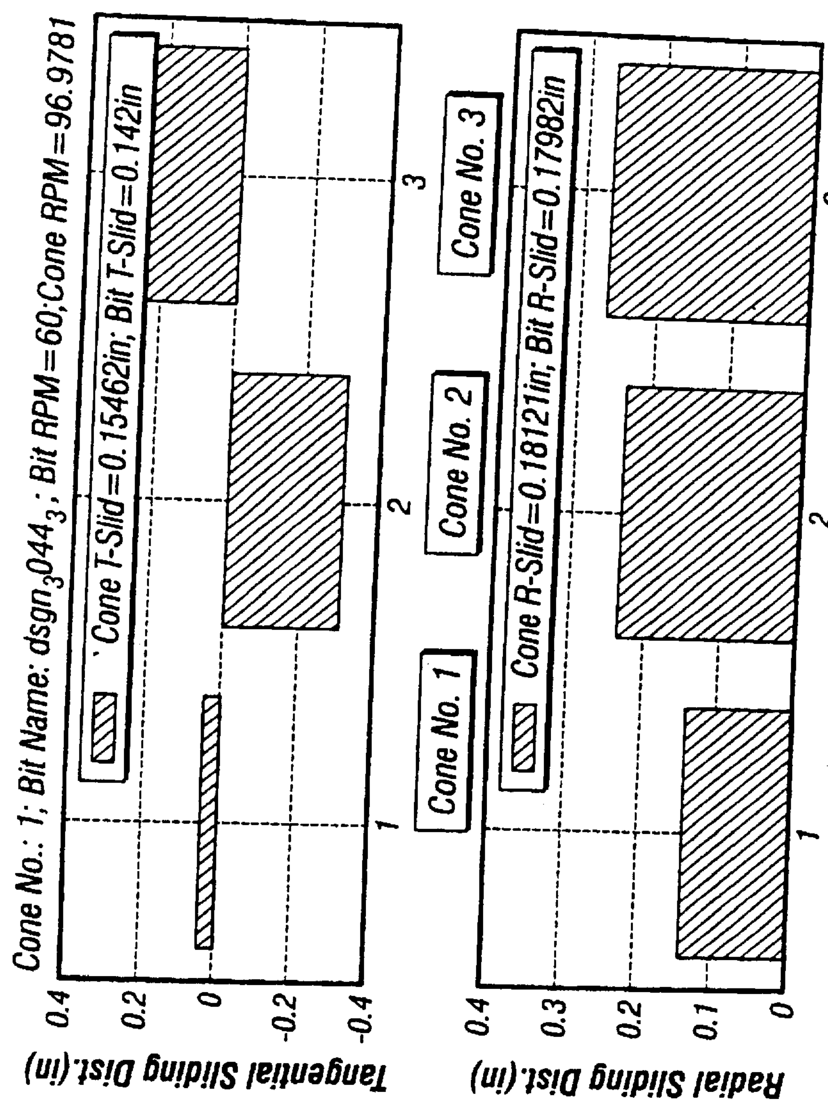

Cone No.: 1; Bit Name: dsgn3044_3; Bit RPM=60;Cone RPM=96.9781
Cone T-Slid=0.15462in; Bit T-Slid=0.142in
Tangential Sliding Dist.(in)
0.4
0.2
0
-0.2
-0.4
1
2
3
Cone No. 1
Cone No. 2
Cone No. 3
Cone R-Slid=0.18121in; Bit R-Slid=0.17982in
Radial Sliding Dist.(in)
0.4
0.3
0.2
0.1
0

FIG. 16D

ROLLER-CONE BITS, SYSTEMS, DRILLING METHODS, AND DESIGN METHODS WITH OPTIMIZATION OF TOOTH ORIENTATION

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of application Ser. No. 09/387,304 filed Aug. 11, 1999 (now issued as U.S. Pat. No. 6,095,262), and therethrough claims priority from provisional application Ser. No. 60/098,442 filed Aug. 31, 1998.

BACKGROUND AND SUMMARY OF THE INVENTION

The present invention relates generally to the drilling of oil and gas wells, or similar drilling operations, and in particular to orientation of tooth angles on a roller cone drill bit.

BACKGROUND: ROTARY DRILLING

Oil wells and gas wells are drilled by a process of rotary drilling, using a drill rig such as is shown in FIG. **10**. In conventional vertical drilling, a drill bit **10** is mounted on the end of a drill string **12** (drill pipe plus drill collars), which may be more than a mile long, while at the surface a rotary drive (not shown) turns the drill string, including the bit at the bottom of the hole.

Two main types of drill bits are in use, one being the roller cone bit, an example of which is seen in FIG. **11**. In this bit a set of cones **16** (two are visible) having teeth or cutting inserts **18** are arranged on rugged bearings on the arms of the bit. As the drill string is rotated, the cones will roll on the bottom of the hole, and the teeth or cutting inserts will crush the formation beneath them. (The broken fragments of rock are swept uphole by the flow of drilling fluid.) The second type of drill bit is a drag bit, having no moving parts, seen in FIG. 12.

Drag bits are becoming increasingly popular for drilling soft and medium formations, but roller cone bits are still very popular, especially for drilling medium and medium-hard rock. There are various types of roller cone bits: insert-type bits, which are normally used for drilling harder formations, will have teeth of tungsten carbide or some other hard material mounted on their cones. As the drill string rotates, and the cones roll along the bottom of the hole, the individual hard teeth will induce compressive failure in the formation.

The bit's teeth must crush or cut rock, with the necessary forces supplied by the "weight on bit" (WOB) which presses the bit down into the rock, and by the torque applied at the rotary drive. While the WOB may in some cases be 100,000 pounds or more, the forces actually seen at the drill bit are not constant: the rock being cut many have harder and softer portions (and may break unevenly), and the drill string itself can oscillate in many different modes. Thus the drill bit must be able to operate for long periods under high stresses in a remote environment.

When the bit wears out or breaks during drilling, it must be brought up out of the hole. This requires a process called "tripping": a heavy hoist pulls the entire drill string out of the hole, in stages of (for example) about ninety feet at a time. After each stage of lifting, one "stand" of pipe is unscrewed and laid aside for reassembly (while the weight of the drill string is temporarily supported by another mechanism). Since the total weight of the drill string may be hundreds of tons, and the length of the drill string may be tens of thousands of feet, this is not a trivial job. One trip can require tens of hours and is a significant expense in the drilling budget. To resume drilling the entire process must be reversed. Thus the bit's durability is very important, to minimize round trips for bit replacement during drilling.

BACKGROUND: DRILL STRING OSCILLATION

The individual elements of a drill string appear heavy and rigid. However, in the complete drill string (which can be more than a mile long), the individual elements are quite flexible enough to allow oscillation at frequencies near the rotary speed. In fact, many different modes of oscillation are possible. (A simple demonstration of modes of oscillation can be done by twirling a piece of rope or chain: the rope can be twirled in a flat slow circle, or, at faster speeds, so that it appears to cross itself one or more times.) The drill string is actually a much more complex system than a hanging rope, and can oscillate in many different ways; see *WAVE PROPAGATION IN PETROLEUM ENGINEERING*, Wilson C. Chin, (1994).

The oscillations are damped somewhat by the drilling mud, or by friction where the drill pipe rubs against the walls, or by the energy absorbed in fracturing the formation: but often these sources of damping are not enough to prevent oscillation. Since these oscillations occur down in the wellbore, they can be hard to detect, but they are generally undesirable. Drill string oscillations change the instantaneous force on the bit, and that means that the bit will not operate as designed. For example, the bit may drill oversize, or off-center, or may wear out much sooner than expected. Oscillations are hard to predict, since different mechanical forces can combine to produce "coupled modes"; the problems of gyration and whirl are an example of this.

BACKGROUND: ROLLER CONE BIT DESIGN

The "cones" in a roller cone bit need not be perfectly conical (nor perfectly frustroconical), but often have a slightly swollen axial profile. Moreover, the axes of the cones do not have to intersect the centerline of the borehole. (The angular difference is referred to as the "offset" angle.) Another variable is the angle by which the centerline of the bearings intersects the horizontal plane of the bottom of the hole, and this angle is known as the journal angle. Thus as the drill bit is rotated, the cones typically do not roll true, and a certain amount of gouging and scraping takes place. The gouging and scraping action is complex in nature, and varies in magnitude and direction depending on a number of variables.

Conventional roller cone bits can be divided into two broad categories: Insert bits and steel-tooth bits. Steel tooth bits are utilized most frequently in softer formation drilling, whereas insert bits are utilized most frequently in medium and hard formation drilling.

Steel-tooth bits have steel teeth formed integral to the cone. (A hardmetal is typically applied to the surface of the teeth to improve the wear resistance of the structure.) Insert bits have very hard inserts (e.g. specially selected grades of tungsten carbide) pressed into holes drilled into the cone surfaces. The inserts extend outwardly beyond the surface of the cones to form the "teeth" that comprise the cutting structures of the drill bit.

The design of the component elements in a rock bit are interrelated (together with the size limitations imposed by the overall diameter of the bit), and some of the design parameters are driven by the intended use of the product. For example, cone angle and offset can be modified to increase or decrease the amount of bottom hole scraping. Many other design parameters are limited in that an increase in one parameter may necessarily result in a decrease of another. For example, increases in tooth length may cause interference with the adjacent cones.

BACKGROUND; TOOTH DESIGN

The teeth of steel tooth bits are predominantly of the inverted "V" shape. The included angle (i.e. the sharpness of the tip) and the length of the tooth will vary with the design of the bit. In bits designed for harder formations the teeth will be shorter and the included angle will be greater. Gage row teeth (i.e. the teeth in the outermost row of the cone, next to the outer diameter of the borehole) may have a "T" shaped crest for additional wear resistance.

The most common shapes of inserts are spherical, conical, and chisel. Spherical inserts have a very small protrusion and are used for drilling the hardest formations. Conical inserts have a greater protrusion and a natural resistance to breakage, and are often used for drilling medium hard formations.

Chisel shaped inserts have opposing flats and a broad elongated crest, resembling the teeth of a steel tooth bit. Chisel shaped inserts are used for drilling soft to medium formations. The elongated crest of the chisel insert is normally oriented in alignment with the axis of cone rotation. Thus, unlike spherical and conical inserts, the chisel insert may be directionally oriented about its center axis. (This is true of any tooth which is not axially symmetric.) The axial angle of orientation is measured from the plane intersecting the center of the cone and the center of the tooth.

BACKGROUND: ROCK MECHANICS AND FORMATIONS

There are many factors that determine the drillability of a formation. These include, for example, compressive strength, hardness and/or abrasivity, elasticity, mineral content (stickiness), permeability, porosity, fluid content and interstitial pressure, and state of under-ground stress.

Soft formations were originally drilled with "fish-tail" drag bits, which sheared the formation away. Roller cone bits designed for drilling soft formations are designed to maximize the gouging and scraping action. To accomplish this, cones are offset to induce the largest allowable deviation from rolling on their true centers. Journal angles are small and cone-profile angles will have relatively large variations. Teeth are long, sharp, and widely-spaced to allow for the greatest possible penetration. Drilling in soft formations is characterized by low weight and high rotary speeds.

Hard formations are drilled by applying high weights on the drill bits and crushing the formation in compressive failure. The rock will fail when the applied load exceeds the strength of the rock. Roller cone bits designed for drilling hard formations are designed to roll as close as possible to a true roll, with little gouging or scraping action. Offset will be zero and journal angles will be higher. Teeth are short and closely spaced to prevent breakage under the high loads. Drilling in hard formations is characterized by high weight and low rotary speeds.

Medium formations are drilled by combining the features of soft and hard formation bits. The rock breaks away (is failed) by combining compressive forces with limited shearing and gouging action that is achieved by designing drill bits with a moderate amount of offset. Tooth length is designed for medium extensions as well. Drilling in medium formations is most often done with weights and rotary speeds between that of the hard and soft formations. Area drilling practices are evaluated to determine the optimum combinations.

BACKGROUND: ROLLER CONE BIT INTERACTION WITH THE FORMATION

In addition to improving drilling efficiency, the study of bottom hole patterns has allowed engineers to prevent detrimental phenomena such as those known as tracking, and gyration. The impressions a tooth makes into the formation depend largely on the design of the tooth, the tangential and radial scraping motions of the tooth, the force and speed with which the tooth impacts the formation, and the characteristics of the formation. Tracking occurs when the teeth of a drill bit fall into the impressions in the formation formed by other teeth at a preceding moment in time during the revolution of the drill bit. Gyration occurs when a drill bit fails to drill on-center. Both phenomena result in slow rates of penetration, detrimental wear of the cutting structures and premature failure of bits. Other detrimental conditions include excessive uncut rings in the bottom hole pattern. This condition can cause gyration, result in slow rates of penetration, detrimental wear of the cutting structures and premature failure of the bits. Another detrimental phenomenon is bit lateral vibration, which can be caused by radial force imbalances, bit mass imbalance, and bit/formation interaction among other things. This condition includes directional reversals and gyration about the hole center often known as whirl. Lateral vibration results in poor bit performance, overgage hole drilling, out-of-round, or "lobed" wellbores, and premature failure of both the cutting structures and bearing systems of bits. (Kenner and Isbell, *DYNAMIC ANALYSIS REVEALS STABILITY OF ROLLER CONE ROCK BITS, SPE*28314, 1994).

BACKGROUND: BIT DESIGN

Currently, roller cone bit designs remain the result of generations of modifications made to original designs. The modifications are based on years of experience in evaluating bit records, dull bit conditions, and bottom hole patterns.

One method commonly used to discourage bit tracking is known as a staggered tooth design. In this design the teeth are located at unequal intervals along the circumference of the cone. This is intended to interrupt the recurrent pattern of impressions on the bottom of the hole. Examples of this are shown in U.S. Pat. No. 4,187,922 and UK application 2,241,266.

BACKGROUND: SHORTCOMINGS OF EXISTING BIT DESIGNS

The economics of drilling a well are strongly reliant on rate of penetration. Since the design of the cutting structure of a drill bit controls the bit's ability to achieve a high rate of penetration, cutting structure design plays a significant role in the overall economics of drilling a well. Current bit designs have not solved the issue of tracking. Complex mathematical models can simulate bottom hole patterns to a limited extent, but they do not suggest a solution to the ever-present problem of tracking. The known angular orientations of teeth designed to improve tooth impact strength leave excessive uncut bottom hole patterns and do not solve the problem of tracking. The known angular orientations of teeth designed to increase bottom hole coverage, fail to optimize tooth orientation and do not solve the problem of tracking. Staggered tooth designs do not prevent tracking of the outermost rows of teeth. On the outermost rows of each cone, the teeth are encountering impressions in the formation left by teeth on other cones. The staggered teeth are just as likely to track an impression as any other tooth. Another disadvantage to staggered designs is that they may cause fluctuations in cone rotational speed, resulting in fluctuations in tooth impact force and increased bit vibration. Bit vibration is very harmful to the life of the bit and the life of the entire drill string.

BACKGROUND: CUTTING STRUCTURE DESIGN

In the publication *A NEW WAY TO CHARACTERIZE THE GOUGING-SCRAPING ACTION OF ROLLER CONE BITS* (Ma, Society of Petroleum Engineers No. 19448, 1989), the author determines that a tooth in the first (heel or gage) row of the drill bit evaluated contacts the formation at −22 degrees (measured with respect to rotation of the cone about its journal) and begins to separate at an angle of −6 degrees. The author determines that the contacting range for the second row of the same cone is from −26 degrees to 6 degrees. The author states that "because the crest of the chisel inserts are always in the parallel direction with the generatrix of the roller cone . . . radial scraping will affect the sweep area only slightly." The author concludes that scraping distance is a more important than the velocity of the cutter in determining performance.

In U.S. Pat. No. 5,197,555, Estes discloses a roller cone bit having opposite angular axial orientation of chisel shaped inserts in the first and second rows of a cone. This invention is premised on the determination that inserts scrape diagonally inboard and either to the leading side (facing in the direction of rotation) or to the trailing side (facing opposite to the direction of rotation). It is noted that the heel row inserts engage the formation to the leading side, while the second row inserts engage the formation to the trailing edge. In one embodiment, the inserts in the heel row are axially oriented at an angle between 30 degrees and 60 degrees, while the inserts in the second row are axially oriented between 300 degrees and 330 degrees. This orientation is designed to provide the inserts with a higher resistance to breakage. In an alternative embodiment, the inserts in the heel row are oriented at an axial angle between 300 degrees and 330 degrees, while the inserts in the second row are axially oriented between 30 degrees and 60 degrees. This orientation is designed to provide the inserts with a broader contact area with the formation for increased formation removal, and thereby an increased rate of penetration of the drill bit into the formation.

SUMMARY: ROLLER-ONE BITS, SYSTEMS, DRILLING METHODS, AND DESIGN METHODS WITH OPTIMIZATION OF TOOTH ORIENTATION

The present application describes bit design methods (and corresponding bits, drilling methods, and systems) in which tooth orientation is optimized jointly with other parameters, using software which graphically displays the linearized trajectory of each tooth row, as translated onto the surface of the cone. Preferably the speed ratio of each cone is precisely calculated, as is the curved trajectory of each tooth through the formation. However, for quick feedback to a design engineer, linear approximations to the tooth trajectory are preferably displayed.

The disclosed innovations, in various embodiments, provide one or more of at least the following advantages:

- The disclosed methods provide a very convenient way for designers to take full advantage of the precision of a computer-implemented calculation of geometries. (The motion over hole bottom of roller cone bit teeth is so complex that only a complex mathematical model and associated computer program can provide accurate design support.)
- The disclosed methods provide convenient calculation of tooth trajectory over the hole bottom during the period when the tooth engages into and disengages from the formation.
- The disclosed methods permit the orientation angle of teeth in all rows to be accurately determined based on the tooth trajectory.
- The disclosed methods permit the influence of tooth orientation changes on bit coverage ratio over the hole bottom to be accurately estimated and compensated.
- The disclosed methods also permit designers to optimally select different types of teeth for different rows, based on the tooth trajectory.

The following patent application describes roller cone drill bit design methods and optimizations which can be used separately from or in synergistic combination with the methods disclosed in the present application. That application, which has common ownership, inventorship, and effective filing date with the present application, is: application Ser. No. 09/387,737, filed Aug. 31, 1999, now U.S. Pat. No. 6,213,225 entitled "Force-Balanced Roller-Cone Bits, Systems, Drilling Methods, and Design Methods" (atty. docket No. SC-9825), claiming priority from U.S. provisional application Ser. No. 60/098,466 filed Aug. 31, 1998.

That nonprovisional application, and its provisional priority application, are both hereby incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWING

The disclosed inventions will be described with reference to the accompanying drawings, which show important sample embodiments of the invention and which are incorporated in the specification hereof by reference, wherein:

FIGS. 1A–1C shows a sample embodiment of a bit design process, using the teachings of the present application.

FIG. 2 shows the tangential and radial velocity components of tooth trajectory, viewed through the cutting face (i.e. looking up).

FIGS. 3A, 3B, 3C, and 3D show plots of planar tooth trajectories for teeth in four rows of a single cone, referenced to the XY coordinates of FIG. 2.

FIGS. 4A and 4B show tangential and radial distances, respectively, for the four tooth trajectories shown in FIGS. 3A–3D.

FIG. 5 is a sectional view of a cone (normal to its axis), showing how the tooth orientation is defined.

FIG. 6 shows time-domain plots of tooth tangential speed, for the five rows of a sample cone, over the duration of the trajectory for each row.

FIGS. 7A and 7B show how optimization of tooth orientation can perturb the width of uncut rings on the hole bottom.

FIGS. 8A and 8B show how optimization of tooth orientation can disturb the tooth clearances.

FIGS. 9A, 9B and 9C show the screen views which a skilled bit designer would see, according to some embodiments of the invention, while working on a bit optimization which included optimization of tooth orientation.

FIG. 10 shows a drill rig in which bits optimized by the teachings of the present application can be advantageously employed.

FIG. 11 shows a conventional roller cone bit, and FIG. 12 shows a conventional drag bit.

FIG. 13 shows a sample XYZ plot of a non-axisymmetric tooth tip.

FIG. 14 shows axial and sectional views of the i-th cone, and illustrates the enumeration of rows and teeth.

FIGS. 15A–15D show how the planarized tooth trajectories vary as the offset is increased.

FIGS. 16A–16D show how the ERSD and ETSD values vary for all rows of a given cone as offset is increased.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The numerous innovative teachings of the present application will be described with particular reference to the presently preferred embodiment (by way of example, and not of limitation).

Overview of Sample Design Process

FIGS. 1A–1C show a sample embodiment of a bit design process, using the teachings of the present application. Specifically, FIG. 1A shows an overview of the design process, and FIGS. 1B and 1C expand specific parts of the process.

First, the bit geometry, rock properties, and bit operational parameters are input (step **102**). Then the 3D tooth shape, cone profile, cone layout, 3D cone, 3D bit, and 2D hole profile are displayed (step **104**).

Since there are two types of rotation relevant to the calculation of the hole bottom (cone rotation and bit rotation), transformation matrices from cone to bit coordinates must be calculated (step **106**). (See FIG. 1B.) The number of bit revolutions is input (step **108**), and each cone is counted (step **110**), followed by each row of teeth for each cone (step **112**). Next, the type of teeth of each row is identified (step **114**), and the teeth are counted (step **116**). Next, a time interval delta is set (step **118**), and the position of each tooth is calculated at this time interval (step **120**). If a given tooth is not "cutting" (i.e., in contact with the hole bottom), then the algorithm continues counting until a cutting tooth is reached (step **122**). The tooth trajectory, speed, scraping distance, crater distribution, coverage ratio and tracking ratios for all rows, cones, and the bit are calculated (step **124**). This section of the process (depicted in FIG. 1B) gives the teeth motion over the hole bottom, and displays the results (step **126**).

Next the bit mechanics are calculated. (See FIG. 1C.) Again transformation matrices from cone to bit coordinates are calculated (step **128**), and the number of bit revolutions and maximum time steps, delta, are input (step **130**). The cones are then counted (step **132**), the bit and cone rotation angles are calculated at the given time step (step **134**), and the rows are counted (step **136**). Next, the 3D tooth surface matrices for the teeth on a given row are calculated (step **138**). The teeth are then counted (step **140**), and the 3D position of the tooth on the hole bottom is calculated at the given time interval (step **142**). If a tooth is not cutting, counting continues until a cutting tooth is reached (step **144**). The cutting depth, area, volume and forces for each tooth are calculated, and the hole bottom model is updated (based on the crater model for the type of rock being drilled). Next the number of teeth cutting at any given time step is counted. The tooth force is projected into cone and bit coordinates, yielding the total cone and bit forces and moments. Finally the specific energy of the bit is calculated (step **146**).

Finally, all results are outputted (step **148**). The process can then be reiterated if needed.

Four Coordinate Systems

Four coordinate systems are used, in the presently preferred embodiment, to define the crest point of a tooth in three dimensional space. All the coordinate system obey the "Right Hand Rule". These coordinate systems—tooth, cone, bit, and hole—are described below.

Local Tooth Coordinates

FIG. 13 shows a sample XYZ plot of a tooth tip (in tooth local coordinates). Tooth coordinates will be indicated here by the subscript t. (Of course, each tooth has its own tooth coordinate system.) The center of the $X_tY_tZ_t$ coordinate system, in the presently preferred embodiment, is located at the tooth center. The coordinate of a tooth's crest point P_t will be defined by parameters of the tooth profile (e.g. tooth diameter, extension, etc.).

Cone Coordinates

FIG. 14 shows axial and sectional views of the i-th cone, and illustrates the enumeration of rows and teeth. Cone coordinates will be indicated here by the subscript c. The center of the cone coordinates is located in the center of backface of the cone. The cone body is fixed with respect to these coordinates, and hence THESE COORDINATES ROTATE WITH THE CONE. (Of course, each cone has its own cone coordinate system.) The axis Z_c coincides with the cone axis, and is oriented towards to the bit center. Cone axes Y_c and X_c, together with axis Z_c, follow the right hand rule. As shown in FIG. 13, four parameters are enough to completely define the coordinate of the crest point of a tooth on cone profile. These four parameters are H_c, R_c, ϕ_c and ϕ_c. For all the teeth on the same row, H_c, R_c, and ϕ_c are the same.

Bit Coordinates

Similarly, a set of bit axes $X_bY_bZ_b$, indicated by the subscript b, is aligned to the bit. The bit is fixed with respect to these coordinates, and hence THESE COORDINATES ROTATE WITH THE BIT. Axis Z_b preferably points toward the cutting face, and axes X_b and Y_b are normal to Z_b (and follow the right-hand rule).

Hole Coordinates

The simplest coordinate system is defined by the hole axes $X_hY_hZ_h$, which are fixed in space. Note however that axes Z_b and Z_h may not be coincident if the bit is tilted. FIG. 2 shows the tangential and radial velocity components of tooth trajectory, viewed through the cutting face (i.e. looking up). Illustrated is a small portion of a tooth trajectory, wherein a tooth's crest (projected into an X_hY_h plane which approximates the bottom of the hole) moves from point A to point B, over an arc distance ds and a radial distance dr.

Transformations

Since all of these coordinate systems are xyz systems, they can be interrelated by simple matrix transformations.

Both the bit and the cones are rotating with time. In order to calculate the position on hole bottom where the crest point of a tooth engages into formation, and the position that the crest point of a tooth disengages from formation, all the teeth positions at any time must be described in hole coordinate system XhYhZh.

The transformation from tooth coordinates $X_tY_tZ_t$, to cone coordinates $X_cY_cZ_c$ can be defined by a matrix Rtc, which is a matrix function of teeth parameters:

$$Rtc=f(H_c, R_c, \theta_c, \phi_c),$$

so that any point P_t in $X_tY_tZ_t$ can be transformed into local cone coordinates $X_cY_cZ_c$ by:

$$P_c=R_{tc}*P_t$$

At time t=0, it is assumed that the plane $X_cO_cZ_c$ is parallel to the bit axis. At time t, the cone has a rotation angle λ around its negative axis ($-Z_c$). Any point on the cone moves to a new position due to this rotation. The new position of P_c in $X_cY_cZ_c$ can be determined by combining linear transforms.

The transform matrix due to cone rotation is R_{cone}:

$$R_{cone}=\cos(\lambda)I+(1-\cos(\lambda))NcNc'+\sin(\lambda)Mc.$$

where N_c is the rotation vector and M_c is a 3*3 matrix defined by N_c.

Therefore, the new position P_{crot} of P_c due to cone rotation is:

$$P_{crot}=R_{cone}*P_c$$

Let R_{cb1}, R_{cb2}, and R_{cb3b} be respective transformation matrices (for cones 1, 2, and 3) from cone coordinate to bit coordinates. (These matrices will be functions of bit parameters such as pin angle, offset, and back face length.) Any point P_{ci} in cone coordinates can then be transformed into bit coordinates by:

$$P_b=R_{cbi}*P_{ci}+P_{coi}\text{ for } i=1, 2, \text{ or } 3.$$

where P_{coi} is the origin of cone coordinates in the bit coordinate system.

The bit is rotating around its own axis. Let us assume that the bit axes and hole axes are coincident at time t=0. At time t, the bit has a rotation angle β. The transform matrix due to bit rotation is:

$$Rbh=\cos(\beta)I+(1-\cos(\beta))NbNb'+\sin(\beta)Mb$$

where Nb is the rotation vector and Mb is a 3*3 matrix defined by Nb. Therefore, any point Pb in bit coordinate system can be transformed into the hole coordinate system $X_hY_hZ_h$ by:

$$Ph=Rbh*Pb.$$

Therefore, the position of the crest point of any tooth at any time in three dimensional space has been fully defined by the foregoing seven equations. In order to further determine the engage and disengage point the formation is modeled, in the presently preferred embodiment, by multiple stepped horizontal planes. (The number of horizontal planes depends on the total number of rows in the bit.) In this way, the trajectory of any tooth on hole bottom can be determined.

Calculation of Trajectories in Bottomhole Plane

With the foregoing transformations, the trajectory of the tooth crest across the bottom of the hole can be calculated. FIGS. 3A, 3B, 3C, and 3D show plots of planar tooth trajectories, referenced to the hole coordinates X_hY_h, for teeth on four different rows of a particular roller cone bit. The teeth on the outermost row (first row) scrapes toward the leading side of the cone. Its radial and tangential scraping distances are similar, as can be seen by comparing the first bar in FIG. 4A with the first bar in FIG. 4B. However for teeth on the second row the radial scraping motion is much larger than the tangent motion. The teeth on the third row scrape toward the trailing side of the cone, and the teeth on the forth row scrape toward the leading side of the cone.

FIGS. 4A and 4B show per-bit-revolution tangential and radial distances, respectively, for the four tooth trajectories shown in FIGS. 3A–3D. Note that, in this example, the motion of the second row is almost entirely radial, and not tangential.

Projection of Trajectories into Cone Coordinates

The tooth trajectories described above are projected on the hole bottom which is fixed in space. In this way it is clearly seen how the tooth scrapes over the bottom. However for the bit manufacturer or bit designer it is necessary to know the teeth orientation angle on the cone coordinate, in order either to keep the elongate side of the tooth perpendicular to the scraping direction (for maximum cutting rate in softer formations) or to keep the elongate side of the tooth in line with the scraping direction (for durability in harder formations). To this end the tooth trajectories are projected to the cone coordinate system. Let $P_1=\{x_1, y_1, Z_1\}_c$ and $P_2=\{x_2, Y_2, z_2\}_c$ be the engage and disengage points on cone coordinate system, respectively, and approximate the tooth trajectory P_1–P2 as a straight line. Then the scraping angle in cone coordinates is:

$$R_1=\sqrt{(x_2-x_1)^2+(y_1+y_2)^2}$$

and

$$\gamma_s=\tan^{-1}\left(\frac{R_1}{z_2-z_1}\right)$$

The teeth can then be oriented appropriately with respect to this angle gamma. For example, for soft formation drilling the tooth would preferably be oriented so that its broad side is perpendicular to the scraping direction, in order to increase its rate of rock removal. In this case, the direction γ_c of the elongate crest of the tooth, in cone coordinates, is normal to γ_s, i.e. $\gamma_c=\gamma_s+\pi/2$. Conversely, for drilling harder formations with a chisel-shaped tooth it might be preferable to orient the tooth with minimum frontal area in the direction of scraping. i.e. with $y_c=y_s$.

Derivation of Equivalent Radial and Tangential Scraping

There are numerous parameters in roller cone design, and experienced designers already know, qualitatively, that changes in cone shape (cone angle, heel angle, third angle, and oversize angle) as well as offset and journal angle will affect the scraping pattern of teeth in order to get a desired action-bottom. One problem is that it is not easy to describe a desired action-on-bottom quantitatively. The present application provides techniques for addressing this need.

Two new parameters have been defined in order to quantitatively evaluate the cone shape and offset effects on tooth scraping motion. Both of these parameters can be applied either to a bit or to individual cones.

(1) Equivalent Tangent Scraping Distance (ETSD) is equal to the total tangent scraping distance of all teeth on a cone (or bit) divided by the total number of the teeth on the cone (or bit).

(2) Equivalent Radial Scraping Distance (ERSD) is equal to the total radial scraping distance of all teeth on a cone (or bit) divided by the total number of the teeth on the cone (or bit).

Both of these two parameters they have much more clear physical meaning than the offset value and cone shape.

Surprisingly, the arcuate (or bulged) shape of the cone primarily affects the ETSD value, and the offset determines the ERSD value. Also surprisingly, the ERSD is not equal to zero even at zero offset.

In other words, the teeth on a bit without offset may still have some small radial scraping effects.

The radial scraping direction for all teeth is always toward to the hole center (positive). However, the tangential scraping direction is usually different from row to row.

In order to use the scraping effects fully and effectively, the leading side of the elongated teeth crest should be orientated at an angle to the plane of the cone's axis, which is calculated as described above for any given row.

FIG. 2 shows the procedure in which a tooth cuts into (point A) and out (point B) the formation. Due to bit offset, arcuate cone shape and bit and cone rotations, the motion from A to B can be divided into two parts: tangent motion ds and radial motion dr. Notice the tangent and radial motions are defined in hole coordinate system XhYh. Because ds and dr vary from row to row and from cone to cone, we derive an equivalent tangent scraping distance (ETSD) and an equivalent radial scraping distance (ERSD) for a whole cone (or for an entire bit).

For a cone, we have

$$ETSD = \frac{\sum_{j}^{Nr} ds_j Nt_j}{Nc}$$

and

$$ERSD = \frac{\sum_{j}^{Nr} dr_j Nt_j}{Nc}$$

where Nc is the total tooth count of a cone and Nr is the number of rows of a cone.

Similarly for a bit, we have

$$ETSD = \frac{\sum_{i}^{3} \sum_{j}^{Nr} ds_{ij} Nt_{ij}}{Nb}$$

and

$$ERSD = \frac{\sum_{i}^{3} \sum_{j}^{Nr} dr_{ij} Nt_{ij}}{Nb}$$

where Nb is the total tooth count of the bit.

FIGS. 15A–15D show how the planarized tooth trajectories vary as the offset is increased. These figures clearly show that with the increase of the offset value, the radial scraping distance is increased. Surprisingly, the radial scraping distance is not equal to zero even if the offset is zero. This is due to the arcuate shape of the cone.

FIGS. 16A–16D show how the ERSD and ETSD values vary for all rows of a given cone as offset is increased. From these Figures, it can be seen that the tangent scraping distance of the gage row, while very small compared to other rows but is not equal to zero. It means that there is a sliding even for the teeth on the driving row. This fact may be explained by looking at the tangent speed during the entry and exit of teeth into and out of the rock. (FIG. 6 shows time-domain plots of tooth tangential speed, for the five rows of a sample cone, over the duration of the trajectory for each row.) During the cutting procedure the tangent speed is not equal to zero except for one instant. Because the sliding speed changes with time, the instantaneous speed is not the best way to describe the teeth/rock interaction.

Note that the tangent scraping directions are different from row to row for the same cone. FIG. 5 is a sectional view of a cone (normal to its axis), showing how the tooth orientation is defined in the present application: the positive direction is defined as the same direction as the bit rotation. This means that the leading side of tooth on one row may be different from that on another row.

The ERSD increases almost proportionally with the increase of the bit offset. However, ERSD is not zero even if the bit offset is zero. This is because the radial sliding speed is not always zero during the procedure of tooth cutting into and cutting out the rock.

Calculation of Uncut Rings, and Row Position Adjustment

FIGS. 7A and 7B show how optimization of tooth orientation can perturb the width of uncut rings on the hole bottom. The width of uncut rings is one of the design constraints: a sufficiently narrow uncut ring will be easily fractured by adjacent cutter action and mud flows, but too large an uncut ring will slow rate of penetration. Thus one of the significant teachings of the present application is that tooth orientation should not be adjusted in isolation, but preferably should be optimized jointly with the width of uncut rings.

Interference Check

Another constraint is tooth interference. In the crowded geometries of an optimized roller cone design, it is easy for an adjustment to row position to cause interference between cones. FIGS. 8A and 8B graphically show how optimization of tooth orientation can disturb the tooth clearances. Thus optimization of tooth orientation is preferably followed by an interference check (especially if row positions are changed).

Iteration

Preferably multiple iterations of the various optimizations are used, to ensure that the various constraints and/or requirements are all jointly satisfied according to an optimal tradeoff.

Graphic Display

The scraping motion of any tooth on any row is visualized on the designer's computer screen. The bit designer has a chance to see quantitatively how large the motion is and in which direction if bit geometric parameters like cone shape and offset are changed.

FIGS. 9A, 9B and 9C show the screen views which a skilled bit designer would see, according to some embodiments of the invention, while working on a bit optimization which included optimization of tooth orientation. These three views show representations of tooth orientation and scraping direction for each tooth row on each of the three cones. This simple display allows the designer to get a feel for the effect of various parameter variations

Calculation of Cone/Bit Rotation Ratio

The present application also teaches that the ratio between the rotational speeds of cone and bit can be easily checked, in the context of the detailed force calculations described above, simply by calculating the torques about the cone axis. If these torques sum to zero (at a given ratio of cone and bit speed), then the given ratio is correct. If not, an iterative calculation can be performed to find the value of this ratio.

However, it should be noted that the exact calculation of the torque on the cones is dependent on use of a solid-body tooth model, as described above, rather than a mere point approximation.

Previous simulations of roller cone bits have assumed that the gage row is the "driving" row, which has no tangential slippage against the cutting face. However, this is a simplification which is not completely accurate. Accurate calculation of the ratio of cone speed to bit speed shows that it is almost never correct, if multiple rows of teeth are present, to assume that the gage row is the driver.

Changes in the tooth orientation angle will not themselves have a large immediate effect on the cone speed ratio. However, the tooth orientation affects the width of uncut rings, and excessive uncut ring width can require the spacing of tooth rows to be changed. Any changes in the spacing of tooth rows will probably affect the cone speed ratio.

Definitions:

Following are short definitions of the usual meanings of some of the technical terms which are used in the present application. (However, those of ordinary skill will recognize whether the context requires a different meaning.) Additional definitions can be found in the standard technical dictionaries and journals.

Drag bit: a drill bit with no moving parts that drills by intrusion and drag.

Mud: the liquid circulated through the wellbore during rotary drilling operations, also referred to as drilling fluid. Originally a suspension of earth solids (especially clays) in water, modern "mud" is a three-phase mixture of liquids, reactive solids, and inert solids.

Nozzle: in a passageway through which the drilling fluid exits a drill bit, the portion of that passageway which restricts the cross-section to control the flow of fluid.

Orientation: the angle of rotation with which a non-axisymmetric tooth is inserted into a cone. Note that a tooth which is axisymmetric (e.g. one having a hemi-spherical tip) cannot have an orientation.

Roller cone bit: a drilling bit made of two, three, or four cones, or cutters, that are mounted on extremely rugged bearings. Also called rock bits. The surface of each cone is made up of rows of steel teeth (generally for softer formations) or rows of hard inserts (typically of tungsten carbide) for harder formations.

According to a disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit, comprising the steps of: adjusting the orientation of at least one tooth on a cone, in dependence on an expected trajectory of said tooth through formation material at the cutting face, in dependence on an estimated ratio of cone rotation to bit rotation; recalculating said ratio, if the location of any row of teeth on said cone changes during optimization; recalculating the trajectory of said tooth in accordance with a recalculated value of said cone speed; and adjusting the orientation of said tooth again, in accordance with a recalculated value of said tooth trajectory.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit, comprising the steps of: calculating the trajectory of at least one tooth on each cone through formation material at the cutting face; and jointly optimizing both the orientations of said teeth and the width of uncut rings on said cutting face, in dependence on said trajectory.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit comprising the steps of: a) adjusting the orientation of at least one row of teeth on a cone, in dependence on an expected trajectory of said tooth through formation material at the cutting face; b) calculating the width of uncut rings of formation material, in dependence on the orientation of said row of teeth, and adjusting the position of said row of teeth in dependence on said calculated width; and c) recalculating the rotational speed of said cone, if the position of said row is changed, and accordingly recalculating said trajectory of teeth in said row.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit, comprising the steps of: calculating the respective trajectories, of at least two non-axisymmetric teeth in different rows of a roller cone bit, through formation material at the cutting face; and graphically displaying, to a design engineer, both said trajectories and also respective orientation vectors of said teeth, as the engineer adjusts design parameters.

According to another disclosed class of innovative embodiments, there is provided: A method of designing a roller cone bit, comprising the steps of: calculating the curved trajectory of a non-axisymmetric tooth through formation material at the cutting face, as the bit and cones rotate; calculating a straight line approximation to said curved trajectory; and orienting said tooth with respect to said approximation, and not with respect to said curved trajectory.

According to another disclosed class of innovative embodiments, there is provided: A roller cone drill bit designed by any of the methods described above, singly or in combination.

According to another disclosed class of innovative embodiments, there is provided: A rotary drilling system, comprising: a roller cone drill bit designed by any of the methods described above, singly or in combination, a drill string which is mechanically connected to said bit; and a rotary drive which rotates at least part of said drill string together with said bit.

According to another disclosed class of innovative embodiments, there is provided: A method for rotary drilling, comprising the actions of: applying weight-on-bit and rotary torque, through a drill string, to a drill bit designed in accordance with any of the methods described above, singly or in combination.

Modifications and Variations

As will be recognized by those skilled in the art, the innovative concepts described in the present application can be modified and varied over a tremendous range of applications, and accordingly the scope of patented subject matter is not limited by any of the specific exemplary teachings given.

For example, the various teachings can optionally be adapted to two-cone or four-one bits.

In the example of FIGS. 9A–9C the crest profiles of all rows except the gage rows are shown as identical (and their crest orientations are indicated by simple ellipses). However, this is not necessary: optionally the designer can be allowed to plug in different tooth profiles for different rows, and the optimization routines can easily substitute various tooth profiles as desired. In particular, various tooth shapes can be selected from a library of profiles, to fit the scraping motion of each row.

In one contemplated class of alternative embodiments, the orientations of teeth can be perturbed about the optimal value, to induce variation between the gage rows of different cones (or within an inner. row of a single cone), to provide some additional resistance to tracking.

Of course the bit will also. normally contain many other features besides those emphasized here, such as gage buttons, wear pads, lubrication reservoirs, etc. etc.

Additional general background, which helps to show the knowledge of those skilled in the art regarding implementations and the predictability of variations, may be found in the following publications, all of which are hereby incorporated by reference: *APPLIED DRILLING ENGINEERING*, Adam T. Bourgoyne Jr. et al., Society of Petroleum Engineers Textbook series (1991), *OIL AND GAS FIELD DEVELOPMENT TECHNIQUES: DRILLING*, J.-P. Nguyen (translation 1996, from French original 1993), MAKING HOLE (1983) and DRILLING MUD (1984), both part of the Rotary Drilling Series, edited by Charles Kirkley.

None of the description in the present application should be read as implying that any particular element, step, or function is an essential element which must be included in the claim scope: THE SCOPE OF PATENTED SUBJECT MATTER IS DEFINED ONLY BY THE ALLOWED CLAIMS. Moreover, none of these claims are intended to invoke paragraph six of 35 USC section 112 unless the exact words "means for" are followed by a participle.

What is claimed is:

1. A method of designing a roller cone bit, comprising the steps of:

inputting initial bit geometry, rock properties, and bit operational parameters;

stepping through a sequence of time intervals and, at each of said time intervals,

mapping the locations of teeth which are cutting at a given time, and

calculating cutting area, volume and forces for each of said teeth which is cutting at said given time, using the results of said mapping step;

adjusting the orientation of said teeth, in accordance with the results of said calculating step.

2. The method of claim 1, wherein each of said teeth on said bit is non-axisymmetric.

3. A roller cone drill bit designed by the method of claim 1.

4. A rotary drilling system, comprising:

a roller cone drill bit designed by the method of claim 1;

a drill string which is mechanically connected to said bit from a surface location; and

a rotary drive which rotates at least part of said drill string together with said bit.

5. A method for rotary drilling, comprising the actions of:

applying weight-on-bit and rotary torque, through, a drill string, to a drill bit designed in accordance with claim 1.

6. A method of designing a roller cone bit, comprising the steps of:

using respective coordinate systems for tooth, cone, bit and hole to define the location of a crest point of a tooth in three dimensional space;

using the locations of respective teeth on a bit to calculate pattern of drilling;

using said pattern of drilling to optimize the orientation of said teeth on said drill bit.

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