第 23 卷　第 2 期
2002 年 3 月
石　油　学　报
ACTA PETROLEI SINICA
Vol. 23　No. 2
Mar.　2002

文章编号:0253-2697(2002)02-0072-05

给定井眼方向的修正轨道设计方法

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摘要: 在定向钻进过程中,井眼方向及其变化规律是井眼轨道监测与控制的关键参数。修正轨道设计作为井眼轨道监控的重要组成部分,对修正设计目标点的井眼方向往往有一定的要求。根据定向钻井工艺技术的特点,本文构造出了具有两个圆弧段和一个直线段的三段式剖面,从而解决了给定井眼方向条件下的修正轨道设计问题,为井眼轨道的有效监控奠定了基础。本文的设计方法避开了求解约束方程组,使得求解过程是一致收敛的,并且所有计算公式在理论上都是精确解,因此其普适性、精确性、稳定性和收敛性得到了保证,可广泛应用于定向井、水平井、大位移井、多目标井的修正轨道设计。

关键词: 钻井理论; 数学模型; 井眼轨道; 设计计算; 定向井; 水平井; 大位移井; 多目标井
中图分类号: TE242　　文献标识码: A

引　言

定向钻井工艺技术的发展,对井眼轨道设计、监测和控制不断提出了更高的要求。在钻井施工过程中,如果实钻轨道与设计轨道之间的偏差超出了允许范围,就需要进行修正设计,使其回到设计轨道上或直接钻向目标点。在地质导向钻井中,如果预计的储层构造和位置与实际不符,而导致中途调整目标点时,也需要进行类似的调整设计。

以往的修正轨道设计方法只要求击中目标,对井眼方向没有限制[1~3]。对于常规的定向井施工,这些方法起到了重要作用。然而,随着钻井技术的不断进步,这样的修正设计概念和方法已不能满足井眼轨道监控的需要。主要表现在:①对于水平井,造斜井段是轨道控制的关键。它不仅要求具有合理的着陆点位置,而且对入靶时的井眼方向具有很高的要求。②在多目标井的设计和施工中,合理的入靶方向是能否成功地击中后续靶点的关键,甚至关系到施工的成败。③由于大位移井具有较长的延伸井段,所以其修正设计往往不是以最终的靶点为目标,而是以设计轨道为基准进行随钻校正。此时,如果不能对井眼方向进行有效的控制,将会增大后续井段轨道控制的难度和工作量,给施工带来不利影响,甚至导致脱靶。实际上,只要修正设计的目标不是最终的靶点,都将存在类似的问题。考虑入靶井眼方向的修正轨道设计问题早已引起了人们的广泛关注。1993 年,刘修善等人曾对水平井的随钻修正设计方法进行过初步探讨[4]。

对于井眼轨道设计问题,一种典型的设计方法是:通过求解有关坐标的约束方程组来确定井身剖面的关键参数。实践证明,这种方法在很多情况下是具有普适性的。但是,约束方程中往往嵌套着多个三角函数,给方程组的求解带来了较大的困难。特别是,在限定了井眼方向的条件下,由于增加了约束方程的数量,使得求解过程的收敛性难以保证。因此,到目前为止,给定井眼方向的修正轨道设计问题尚未得到较好地解决。

根据微分几何原理,提出了这种复杂情况下的井眼轨道设计方法。由于避开了求解约束方程组,使得求解过程是一致收敛的,为井眼轨道的有效监控奠定了基础。

1　剖面模型及约束条件

尽管很多参数都与井眼轨道的监测和控制有关,但是在定向钻进施工过程中,井眼方向(即井斜角和方位

基金项目:国家 863 青年基金项目(820-Q-04)。
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角)及其变化规律是最直接的监控参数。然而,井眼方向的变化规律不是孤立的,它与井下工具的特性、造斜工艺以及控制方法等密切相关。目前,多采用滑动钻进方式下的导向钻具组合来调整和校正井眼轨道,由于其造斜特性比较稳定,因此所钻出的井眼轨道接近于空间圆弧。

井眼轨道的设计应与钻井工艺技术相适应,并依据一定的数学模型。根据修正轨道的特点和设计要求,选用由空间圆弧和直线段所组成的井身剖面作为修正轨道的设计模型。对于按照给定的井眼方向击中目标的修正轨道设计问题,“空间圆弧段 —直线段 —空间圆弧段”剖面是最简单的数学模型。由于该剖面有两个圆弧段,所以这种设计方法可称之为双圆弧法。通常,这两个空间圆弧不位于同一个斜平面内(如图 1 所示)。

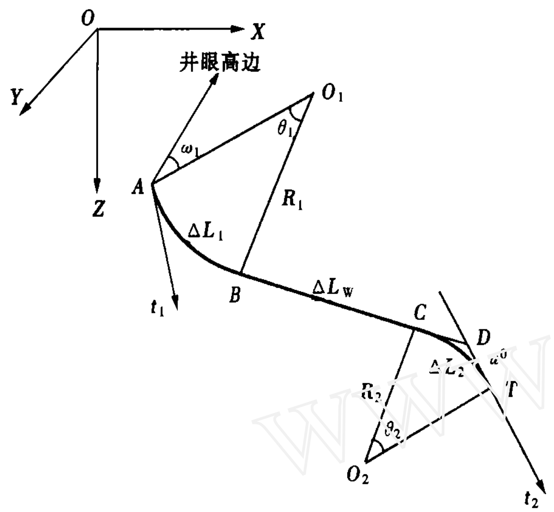

图 1　修正轨道的数学模型

Fig. 1　Mathematical model of the correction path

根据设计要求和剖面模型,修正轨道应满足如下约束方程

$$\sum_{i=1}^{3}\Delta\alpha_i = \alpha_T - \alpha_A \qquad (1) \qquad\qquad \sum_{i=1}^{3}\Delta\phi_i = \phi_T - \phi_A \qquad (2)$$

$$\sum_{i=1}^{3}\Delta X_i = X_T - X_A \qquad (3) \qquad\qquad \sum_{i=1}^{3}\Delta Y_i = Y_T - Y_A \qquad (4)$$

$$\sum_{i=1}^{3}\Delta Z_i = Z_T - Z_A \qquad (5)$$

式中　α、ϕ、X、Y 和 Z 分别表示井斜角、方位角、北坐标、东坐标和垂深;$\Delta\alpha$、$\Delta\phi$、ΔX、ΔY 和 ΔZ 分别为各井段上 α、ϕ、X、Y 和 Z 的增量;下标 A 和 T 分别表示修正设计的起始点和目标点。

在上述的 5 个约束方程中,各参数之间并不是相互独立的。研究表明:由于方程组中嵌套着多个三角函数,使求解的收敛性受到了影响,导致迭代计算常常是发散的,而使设计过程无法继续进行。为了解决这个难题,提出了一种新的设计思想和求解方法。该方法既满足式(1)～式(5)的条件,又避开了直接求解上述的约束方程组,从而使求解过程的收敛性和稳定性得到了充分的保证。

2　设计方法

由于目标点的坐标和井眼方向是预先给定的, 所以根据给定的井眼方向,过 T 点可以作出井眼轨道的切线。在井眼前进的相反方向上,取长度 u^0 确定出 D 点的位置,其坐标为

$$X_D = X_T - u^0 \sin\alpha_T \cos\phi_T \qquad (6)$$

$$Y_D = Y_T - u^0 \sin\alpha_T \cos\phi_T \qquad (7)$$

$$Z_D = Z_T - u^0 \cos\alpha_T \qquad (8)$$

确定了 D 点的坐标之后,它与起始点 A 的井眼切线构成了一个空间斜平面。在这个斜平面上设计井眼轨道,就将三维问题转化成了二维问题。

如图 2 所示。以起始点 A 为原点,建立右手直角坐标系 A - $\xi\eta\zeta$。ξ 轴指向轨道的前进方向,η 轴在斜平面内指向第一圆弧段的内法线方向(即垂直于 ξ 轴且指向目标点一侧),ζ 轴由右手法则确定,它指向斜平面的法线方向。为叙述方便,设 ξ、η 和 ζ 坐标轴上的单位坐标矢量分别为 a、b、c。

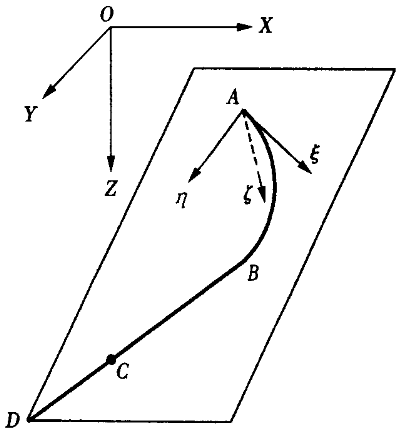

图 2　斜平面内的井眼轨道

Fig. 2　Well path in the inclined plane

由几何关系知,矢量 a 和连接点 A 点、D 点的单位矢量 d 可分别由式(9)和式(10)确定。

$$\begin{cases} a_X = \sin\alpha_A\cos\phi_A \\ a_Y = \sin\alpha_A\sin\phi_A \\ a_Z = \cos\alpha_A \end{cases} \quad (9) \qquad \begin{cases} d_X = (X_D - X_A)/d \\ d_Y = (Y_D - Y_A)/d \\ d_Z = (Z_D - Z_A)/d \end{cases} \quad (10)$$

其中 $d = \sqrt{(X_D - X_A)^2 + (Y_D - Y_A)^2 + (Z_D - Z_A)^2}$

由于 c = a ×d ,所以 c 的方向余弦为

$$\begin{cases} c_X = (a_Y d_Z - d_Y a_Z)/c \\ c_Y = (a_Z d_X - d_Z a_X)/c \\ c_Z = (a_X d_Y - d_X a_Y)/c \end{cases} \quad (11)$$

其中 $c = \sqrt{(a_Y d_Z - d_Y a_Z)^2 + (a_Z d_X - d_Z a_X)^2 + (a_X d_Y - d_X a_Y)^2}$

又由于 b = c ×a , a ⊥c ,且均为单位矢量,所以 b 的方向余弦为式(12) 。进而,根据坐标系的转换关系,得式(13)

$$\begin{cases} b_X = c_Y a_Z - a_Y c_Z \\ b_Y = c_Z a_X - a_Z c_X \\ b_Z = c_X a_Y - a_X c_Y \end{cases} \quad (12) \qquad \begin{bmatrix} \xi_D \\ \eta_D \\ \zeta_D \end{bmatrix} = \begin{bmatrix} a_X & a_Y & a_Z \\ b_X & b_Y & b_Z \\ c_X & c_Y & c_Z \end{bmatrix} \begin{bmatrix} X_D - X_A \\ Y_D - Y_A \\ Z_D - Z_A \end{bmatrix} \quad (13)$$

根据图3所示的几何关系,第一圆弧段的弯曲角为

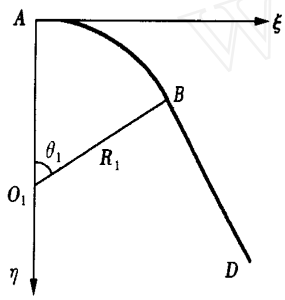

图3 局部坐标系下的修正轨道

Fig. 3 Correction path in the local coordinate system

$$\mathrm{tg}\frac{\theta_1}{2} = \begin{cases} \dfrac{\xi_D - \sqrt{\xi_D^2 + \eta_D^2 - 2R_1\eta_D}}{2R_1 - \eta_D}, & 当\ \eta_D \neq 2R_1 \\ \dfrac{\eta_D}{2\xi_D}, & 当\ \eta_D = 2R_1 \end{cases} \quad (14)$$

式(14)应满足 $\xi_D^2 + \eta_D^2 - 2R_1\eta_D \geq 0$。如果出现小于零的情况,则说明该剖面不存在。

上述过程是在用 u^0 确定 D 点位置的条件下进行的,因此这种方法是一个迭代求解过程。此时,第二圆弧段新的切线段长度为

$$u = R_2\mathrm{tg}\frac{\theta_2}{2} \quad (15)$$

其中 $\cos\theta_2 = \cos\alpha_w\cos\alpha_T + \sin\alpha_w\sin\alpha_T\cos(\phi_T - \phi_w)$, $\cos\alpha_w = a_Z\cos\theta_1 + b_Z\sin\theta_1$, $\mathrm{tg}\phi_w = \dfrac{a_Y + b_Y\mathrm{tg}\theta_1}{a_X + b_X\mathrm{tg}\theta_1}$,式中 θ_2 为第二圆弧段的弯曲角; α_w、ϕ_w 分别为斜直井段的井斜角和方位角。

对于预先给定的计算精度 ε,若满足 $|u - u^0| < \varepsilon$,则迭代计算结束。否则,令 $u^0 = u$,重复上述计算,直到满足精度要求为止。

迭代计算完成后,可分别按以下公式计算出各井段的长度

$$\Delta L_1 = CR_1\theta_1 \quad (16) \qquad \Delta L_w = \sqrt{\xi_D^2 + \eta_D^2 - 2R_1\eta_D} - u \quad (17) \qquad \Delta L_2 = CR_2\theta_2 \quad (18)$$

其中 $C = \begin{cases} \dfrac{\pi}{180}, & 当弯曲角以“度”为单位时 \\ 1, & 当弯曲角以“弧度”为单位时 \end{cases}$

至此,便确定出了修正设计轨道上的关键参数。

3 轨道计算

在进行井眼轨道设计时,求得了剖面的关键参数之后,还需要计算出诸点的轨道参数。

对于斜直井段,主要参数的计算公式为

$$\alpha = \alpha_B \qquad (19) \qquad\qquad \phi = \phi_B \qquad (20) \qquad\qquad \kappa_\alpha = \kappa_\phi = 0 \qquad (21)$$

$$\begin{bmatrix} X - X_B \\ Y - Y_B \\ Z - Z_B \end{bmatrix} = (L - L_B)\begin{bmatrix} \sin\alpha_B \cos\phi_B \\ \sin\alpha_B \sin\phi_B \\ \cos\alpha_B \end{bmatrix} \qquad (22)$$

可以用式(13)所表述的基本关系式进行圆弧井段的轨道计算。但是,借助于装置角来描述圆弧井段更方便,且具有普适性。为此,需要先计算出圆弧井段的弯曲角和初始装置角

$$\theta = \frac{L - L_A}{CR_1} \qquad (23) \qquad\qquad \mathrm{tg}\,\omega_1 = \frac{\sin(\phi_w - \phi_A)}{\cos\alpha_A\left[\cos(\phi_w - \phi_A) - \dfrac{\mathrm{tg}\,\alpha_A}{\mathrm{tg}\,\alpha_w}\right]} \qquad (24)$$

进而,轨道参数可用下述公式计算[5]

$$\cos\alpha = \cos\alpha_A\cos\theta - \sin\alpha_A\sin\theta\cos\omega_1 \qquad (25)$$

$$\mathrm{tg}\,\phi = \frac{\sin\alpha_A\sin\phi_A + (\cos\alpha_A\sin\phi_A\cos\omega_1 + \cos\phi_A\sin\omega_1)\,\mathrm{tg}\,\theta}{\sin\alpha_A\cos\phi_A + (\cos\alpha_A\cos\phi_A\cos\omega_1 - \sin\phi_A\sin\omega_1)\,\mathrm{tg}\,\theta} \qquad (26)$$

$$\kappa_\alpha = \frac{\kappa_1}{\sin\alpha}(\cos\alpha_A\sin\theta + \sin\alpha_A\cos\theta\cos\omega_1) \qquad (27)$$

$$\kappa_\phi = \kappa_1\frac{[\sin\omega_1\cos(\phi - \phi_A) - \cos\omega_1\sin(\phi - \phi_A)\cos\alpha_A]^2}{\sin\alpha_A\sin\omega_1\cos^2\theta} \qquad (28)$$

$$\begin{bmatrix} X - X_A \\ Y - Y_A \\ Z - Z_A \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix}\begin{bmatrix} R_1\sin\theta \\ R_1(1 - \cos\theta) \\ 0 \end{bmatrix} \qquad (29)$$

其中　$T_{11} = \sin\alpha_A\cos\phi_A$; $T_{12} = \cos\alpha_A\cos\phi_A\cos\omega_1 - \sin\phi_A\sin\omega_1$; $T_{13} = -\cos\alpha_A\cos\phi_A\sin\omega_1 - \sin\phi_A\cos\omega_1$; $T_{21} = \sin\alpha_A\sin\phi_A$; $T_{22} = \cos\alpha_A\sin\phi_A\cos\omega_1 + \cos\phi_A\sin\omega_1$; $T_{23} = -\cos\alpha_A\sin\phi_A\sin\omega_1 + \cos\phi_A\cos\omega_1$; $T_{31} = \cos\alpha_A$; $T_{32} = -\sin\alpha_A\cos\omega_1$; $T_{33} = \sin\alpha_A\sin\omega_1$。

可以验证,式(27)和式(28)满足如下的井眼曲率计算公式

$$\kappa = \sqrt{\kappa_\alpha^2 + \kappa_\phi^2\sin^2\alpha} \qquad (30)$$

对于第二圆弧段的计算,只需将上述公式的下标作相应的替换即可。

4　实例验证与分析

某水平井设计的着陆点井斜角为 88°,方位角为 50°。当钻至井斜角为 76°,方位角为 54 时,距着陆点的垂深为 12m、水平位移为 78m、平移方位为 47.5°。如果上部井段和下部井段分别用 8°/30m 和 10°/30m 造斜率的导向钻具施工,如何设计修正轨道才能按设计要求准确着陆。

经迭代计算得,$\theta_1 = 11.95°$,$\theta_2 = 8.91°$,$\alpha_w = 81.95°$,$\phi_w = 43.43°$,$u = 13.39$m。根据相关公式计算出的其它参数分别为 $\Delta L_1 = 44.82$m,$\Delta L_w = 7.60$m,$\Delta L_2 = 26.73$m,$\omega_1 = 298.73°$,$\omega_2 = 47.56°$。其计算结果见表 1。为简洁,表 1 中的坐标参数均以修正设计的起始点为基准。

如果不考虑对井眼方向的约束,按照传统的"圆弧段—斜直段"剖面设计(采用 8°/30m 的造斜率),则可以得到如表 2 所示的设计结果。由此可以看出:尽管这两种方法所设计出的总井段长度十分接近,但传统设计方法所得到的井斜角和方位角与期望值分别相差 4.8°和 4.81°。如果以如此大的偏差着陆,将导致水平井段的施工无法正常进行。显然,这种设计结果在工程上是不能被接受的。

表 1　修正轨道的设计结果

Table 1　Planned results of the correction path

井深 (m)	井斜角 (°)	方位角 (°)	北坐标 (m)	东坐标 (m)	垂深 (m)	平移 (m)	平移方位 (°)	井斜率 (°/30m)	方位率 (°/30m)
0.00	76.00	54.00	0.00	0.00	0.00	0.00	—	3.85	- 7.23
10.00	77.29	51.60	5.88	7.75	2.31	9.73	52.80	3.91	- 7.15
20.00	78.61	49.23	12.11	15.29	4.40	19.50	51.60	3.97	- 7.08
30.00	79.94	46.88	18.68	22.59	6.26	29.31	50.41	4.03	- 7.02
40.00	81.29	44.55	25.57	29.65	7.89	39.16	49.23	4.07	- 6.97
44.82	81.95	43.43	29.00	32.97	8.59	43.91	48.66	4.09	- 6.94
50.00	81.95	43.43	32.72	36.49	9.32	49.02	48.12	0.00	0.00
52.42	81.95	43.43	34.46	38.14	9.66	51.40	47.90	6.75	7.45
60.00	83.66	45.31	39.84	43.40	10.61	58.91	47.45	6.78	7.40
70.00	85.92	47.76	46.69	50.63	11.51	68.87	47.32	6.81	7.34
79.15	88.00	50.00	52.70	57.51	12.00	78.00	47.50	6.82	7.32

表 2　传统设计方法的计算结果

Table 2　Calculated results of the traditional planning method

井深 (m)	井斜角 (°)	方位角 (°)	北坐标 (m)	东坐标 (m)	垂深 (m)	平移 (m)	平移方位 (°)	井斜率 (°/30m)	方位率 (°/30m)
0.00	76.00	54.00	0.00	0.00	0.00	0.00	—	5.02	- 6.42
10.00	77.68	51.87	5.87	7.77	2.28	9.74	52.93	5.07	- 6.34
20.00	79.38	49.77	12.06	15.37	4.27	19.53	51.87	5.11	- 6.26
30.00	81.09	47.70	18.56	22.77	5.96	29.38	50.82	5.15	- 6.20
40.00	82.81	45.64	25.35	29.97	7.36	39.26	49.77	5.18	- 6.14
42.23	83.20	45.19	26.91	31.55	7.63	41.47	49.54	5.19	- 6.13
50.00	83.20	45.19	32.34	37.02	8.55	49.16	48.86	0.00	0.00
60.00	83.20	45.19	39.34	44.07	9.74	59.07	48.24	0.00	0.00
70.00	83.20	45.19	46.34	51.11	10.92	68.99	47.80	0.00	0.00
79.08	83.20	45.19	52.70	57.51	12.00	78.00	47.50	0.00	0.00

5　结　论

(1) 考虑入靶井眼方向的修正轨道设计问题早已引起了广泛的关注。只要修正设计的目标不是最终的靶点,那么对井眼方向的有效控制比中靶的坐标要求往往显得更为重要。

(2) 根据定向钻井工艺技术的特点,本文用圆弧段和直线段构造出三段式的修正设计轨道,提出了给定井眼方向的修正轨道设计方法。从而,为井眼轨道的有效监控奠定了基础,可广泛应用于定向井、水平井、大位移井、多目标井的修正轨道设计。

(3) 本文的设计方法满足约束条件,但避开了求解约束方程组,从而使求解过程的收敛性和稳定性得到了充分的保证。

(4) 文中的所有计算公式在理论上都是精确解,具有普遍适用性。大量的算例验证了该方法的计算稳定性和计算精度。

参　考　文　献

[1]　McMillian W H. Planning the directional well — a calculation method[J]. J. Pet. Tech., 1981, 33(6): 952～962.

[2]　Brown D E. Programmed math keeps directional drilling on target[J]. Oil & Gas Journal, 1980, 78(12): 164～167.

[3]　白家祉,苏义脑. 定向钻井过程中的三维井身随钻修正设计与计算[J]. 石油钻采工艺, 1991, 13(6): 1～4.

[4]　刘修善,王珊,周大千. 水平井轨道随钻修正设计[J]. 石油钻探技术, 1993, 21(2): 27～30.

[5]　刘修善,郭钧. 空间圆弧轨道的描述与计算[J]. 天然气工业, 2000, 20(5): 44～47.

(收稿日期 2000-12-25　　改回日期 2001-04-23　　编辑　张君娥)

searchers to evaluate a reservoir. Since the present model is sensitive to the variation of saturation ,mud property , drilling condition and so on ,a reservoir can be evaluated through matching time dependent field logging data. Original water saturation(or true formation resistivity) and mud cake permeability are regarded as unknown parameters to be determined from the inversion routine. Field applications for dual-induction logging illustrate that the present model is a reasonable and efficient method for reservoir evaluation.

Key words :well logging ;inversion ;invasion ;time ;resistivity ;saturation

THE DEVELOPMENT WELL-PATTERN OF LOW AND ANISOTROPIC PERMEABLITY RESERVOIRS

DING Yun-hong ,et al. *(China University of Geosciences , Beijing 100083 , China)* ACTA 2002 ,23(2) :64～67

Abstract : Low permeability reservoirs commercial development is usually obtained by fracturing stimulation. The development of low permeability reservoirs is different from that of normal reservoirs because of the appearance of hydraulic fractures. Severe heterogeneity usually exist due to the permeability anisotropy resulted from developed or tensile natural fractures in low permeability reservoirs. As a result ,it is necessary to take into account the effect of heterogeneity of both hydraulic fractured and permeability while planing well pattern. This paper presents the research of inverted nine-spot pattern which is normally used in the development of low permeability reservoirs and modified inverted nine-spot pattern and rectangular pattern. It shows that higher oil recovery and economic efficiency would be achieved by adopting the rectangular pattern if the azimuth of hydraulic fracture is clearly known.

Key words :low permeability ;development well pattern ;rectangle ;inverted nine-spot ;anisotropy

PRODUCTIVITY CALCULATION METHOD OF FRACTURED HORIZONTAL WELLS IN LOW PERMEABILITY OIL OR GAS FIELD

NING Zheng-fu ,et al. *(Petroleum University , Beijing 102200 , China)* ACTA 2002 ,23(2) :68～71

Abstract : This paper revise the formula presented and deduce a new formula on productivity forecast of fractured horizontal well ,applying potential function principles ,superposition principle ,and mathematical method for solving matrix ,considering flow resistance and pressure drop in fracture. As an example ,the productivity of fractured horizontal well in a low permeability gas reservoir has been tested by using this formula ,and some useful conclusions have been drawn from comparing and analyzing some factors. These conclusions are instructive in designing fractured horizontal well for low permeability reservoir.

Key words :low permeability ;horizontal well ;fracture ;productivity forecast ;flow resistance

PETROLEUM ENGINEERING

A NEW METHOD OF PATH-CORRECTION PLANNING WITH THE DESIRED DIRECTION

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ACTA 2002 ,23(2) :72～76

Abstract : During the process of directional drilling ,the direction of well trajectory and its change are key parameters to monitor and control a well trajectory. As an important part of monitoring and controlling a well trajectory ,the path-correction planning is generally required to reach a desired direction at its target. According to the characteristics of directional drilling technology ,a three-section profile with two planar turns and one straight line is constructed in this paper to solve the problem on path-correction planning with the given direction in theory ,which lays a foundation for effectively monitoring and controlling a well trajectory. The solving process of the design method proposed in this paper is uniform convergent due to avoiding solving the constraint equations set. All of the formulas are theoretically exact solutions, so the universal significance, computational accuracy, stability and convergence have been fully guaranteed. This method can be widely applied to planning directional wells, horizontal wells, extended-reach wells and multiple target wells while drilling.

Key words: drilling theory; mathematical model; wellbore trajectory; design calculation; directional well; horizontal well; extended-reach well; multiple target well

PROBLEM OF DOUBLE AND TRIPLE BENT PDM EQUIVALENT TO SINGLE BENT PDM

SU Yi-nao, TANG Xue-ping *(Research Institute of Petroleum Exploration and Development, PetroChina, Beijing* 100083, *China)* ACTA 2002, 23(2): 77～81

Abstract: The method and formula of simplifying double bent PDM to equivalent single bent PDM is presented and the integrated equations applied to DKO and DTU are derived and a step equivalent method of simplifying double bent (mutibent) PDM to single bent PDM is provided. The difference and relationship between the deflecting force of bit and limiting curvature, build-up rate, etc in concept is discussed in this paper through limiting curvature method. These methods and results can be used to explain doubtful points of theory existed and to guide the design of structure and behavior of double bent (mutibent) PDM assembly in horizontal drilling.

Key words: horizontal well; double bent PDM; equivalent problem; limiting curvature; build-up rate

WAX PRECIPITATION PREDICTION BY THERMODYNAMIC MODEL OF GAS-LIQUID-SOLID THREE PHASES EQUILIBRIUM

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Abstract: The heavy organic substances, such as wax, resin and asphaltene will precipitate as a solid phase, causing serioius problems to operate the oil and gas fields, when thermodynamic conditions of temperature, pressure or composition are changed in the process of oil and gas production. A thermodynamic model of the gas-liquid-solid three phases equilibria is presented, combing an equation of state with a solution theory. A regular solution theory is used to account for the non-ideality of the solid mixture, and an equation of state describes both gas and liquid phase behavior. A wax precipitation calculation for a live oil system is conducted using the thermodynamic model. The calculation results demonstrate that the pressure has a greater influence on that wax precipitation. The effect of pressure on wax precipitation temperature is greater below the saturate pressure than the above saturate pressure.

Key words: gas-liquid-solid; wax precipitation; thermodynamic model; equation of state; regular solution

THE LAW OF VELOCITY DISTRIBUTION OF BINGHAM FLUID'S FLOWING IN THE ENCIRCLE PIPE

LI Zhao-min, et al. *(Petroleum University, Donging* 257061, *China)* ACTA 2002, 23(2): 87～91

Abstract: In this article, combinating Bingham fluid's constitutive equation with momentum equation, the velocity distribution of Bingham fluid's flowing in the encircle pipe is obtained by means of dimension analysis, which is under the condition of laminar flowing. Moreover the effects of some parameters such as yield stress and pressure gradient on the velocity profile have been discussed: the difference of velocity distribution between Bingham fluid and Newtonian fluid increases with yield stress, the width of flow nucleus also increases with yield stress; as pressure