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RESEARCH NOTE

The Research on the Biggest Borehole Curvature that Allowed through for the Rotating Casing

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ABSTRACT

With the development of highly-deviated well cementing techniques, rotating casing cementing technology has got more and more attention. The rotating casing technique can improve the displacement efficiency of cement paste, and then enhance the quality of well cementation. In the stuck section, the rotating casing can redress the well to make the casing run sequentially. The casing endures shear stress in rotating, besides axial stress, bending stress, circumferential stress and radial stress which are produced by inside and outside casing pressure stress. These forces make it more complicated when calculate the maximum curvature in rotating condition than that without rotation. The paper, by analyzing the casing stresses in rotating condition, assumes a stress model of the casing infinitesimal for rotating casing. It puts forward the calculation method for the maximum allowable borehole curvature in casing bucking deformation, or when casing couplings and thread seal fail under rotating condition. It also determines the biggest borehole curvature that allowed though, laying a base for the design and construction of the highly-deviated well casing.

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1. INTRODUCTION

As the exploration of oil reservoir develops in depth and in quantity, the development of highly-deviated well technology has become the mainstream trend of the well drilling in shoals,sea and lean oil layers. There are a lot of technical challenges and cementing quality problems for highly-deviated well cementation. The adoption of rotating casing technique can improve the displacement efficiency of cement paste, and then enhance the quality of well cementation. In the stuck section, rotating casing can redress the well to make the casing run sequentially, [1]. The force is very complex in the rotating casing of highly-deviated well. In the bending section, the flexion deformity of the casing body, the strength fracture of the collar point and the seal failure of the thread are so easy to happen that casing can't run smoothly. Therefore, the reasonable calculation of the biggest borehole curvature that allowed through becomes very important. Many scholars have put forward some methods of calculating the biggest borehole curvature that allowed through. A computational formula has been recommended by API and IADC, [2]. However, the formula has such defects: (1) it doesn't consider the strength difference between the casing body and the thread joint; (2) it doesn't consider the effect of the effective axial force; (3) the date range of the safety factor and the stress concentration factor in the formula is very large, and then the error maybe big, et al. [3]. Professor Zhiyong Han has also recommended a computational formula of the biggest borehole curvature that allowed through [4] which has solved all the problems in the computational formula recommended by the API and IADC. Other than, it doesn't consider the impacts of rotating casing, the burst and collapse pressure of the casing on the ultimate curvature. Whether the casing can run smoothly through the highly-deviated well section or not affects the follow-up work of the highly-deviated well cementation. Whereas the problems existing in the predictive formulas, the research on the biggest

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borehole curvature that allowed through for the rotating casing in the highly-deviated well is quite significant.

This paper plans to build the maximum stress model of the casing infinitesimal for rotating casing, with the help of the bending deformation theory and strength theory in the mechanics of materials [5]. It is also plan to study the biggest boreholecurvature that allowed through for the rotating casing in the highly-deviated well, in order to guide the design and construction of the highly-deviated well casing.

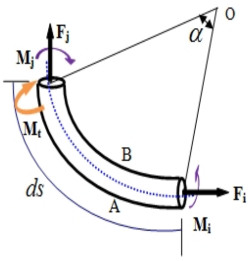

Figure 1. The curved section infinitesimal for the rotating casing

2. THE ESTABLISHMENT OF MAXIMUM STRESS MODEL OF BENDING UNIT FOR THE ROTATING CASING

When the casing string runs through curved sections for the rotating casing, the stress on the casing infinitesimal is shown in Figure 1.

When casing is bended, the side of the pipe body and coupling bears tensile stress, and the opposite under compressive stress, the angle difference between the direction of stresses is 180°, the stress of the casing string is asymmetrical, cyclic and alternating when rotating, [6-8], which is shown in Figure 2. In the figure：

Average stress：σ_m=σ_b，σ_b is axial stress；

Stress amplitude：σ_a=（σ_{max}-σ_{min}）/2，and so the σ_a is the bending stress of casing.

The pipe body and coupling of bending section are cycled fatigue failure rarely, but plastic failure of tube body, thread damage of joint and seal failure are more easily due to the slow rotation speed and quick tripping during the rotating casing, [9-11]. According to the theory of material damage [5], when the axial tensile (or pressure) stress at or just above the coupling or the pipe body of ultimate stress, tension side or compression side fail firstly, casing plastic deformation or thread slippage will not appear. From the view of the whole fracture surface, it can be concluded that only a small part of the two circular elements coop sreach failure state nor the most part. Casing stresses are shown in Figure 3.

The stresses of the running cases in the rotating condition are: axial tensile stress σ_L which equals effective axial stress plus bending stress、radial stress σ_r and circumferential stress σ_t produced by collapse stress and internal pressure, shearing stress τ. The stress state of casing unit is shown in Figure 4.

We know in the Figure 4: There is no shearing stress in the plane which radial stress σ_r vertical. Writing off the radial stress σ_r as one of primary stresses σ_3； In the plane of axial stress and circumferential stress, the axial tensile stress, circumferential stress and shear stress existall at once. The stress is shown in the Figure 5.

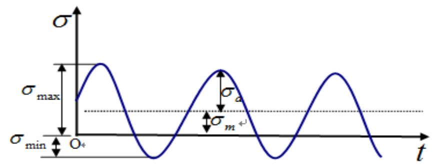

Figure 2. Characteristics of stress under asymmetrical, circling, and alternating condition

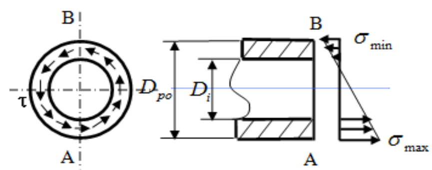

Figure 3. Casing buckling infinitesimal

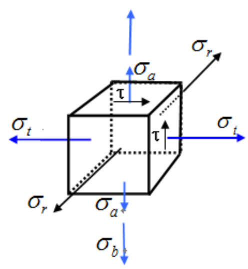

Figure 4. The stress state of one point under three-dimensional stress state

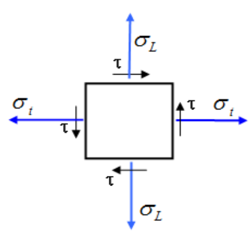

Figure 5. Biaxial stress state composed of axial stress and circumferential stress

Based on the theory of biaxial stress ellipse, the two principal stresses in the Figure 5 can be concluded as:

$$\begin{cases} \sigma_1 = \dfrac{\sigma_L + \sigma_t}{2} + \sqrt{\dfrac{(\sigma_L - \sigma_t)^2}{4} + \tau^2} \\ \sigma_2 = \dfrac{\sigma_L + \sigma_t}{2} - \sqrt{\dfrac{(\sigma_L - \sigma_t)^2}{4} + \tau^2} \end{cases} \quad (1)$$

Based on the fourth strength theory, the formula of plastic deformation can be concluded as:

$$\sigma_s = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1\sigma_2 - \sigma_2\sigma_3 - \sigma_3\sigma_1} \quad (2)$$

Take σ_1, σ_2, σ_3 into the Formula (2):

$$\sigma_L = \frac{\sigma_t + \sigma_r}{2} + \sqrt{\sigma_s^2 - \frac{1}{4}(\sigma_r - \sigma_t)^2 - 3\tau^2} \quad (3)$$

Take $\sigma_L = \sigma_b + \sigma_a$ into the Formula (3):

$$\sigma_a = \frac{\sigma_t + \sigma_r}{2} + \sqrt{\sigma_s^2 - \frac{1}{4}(\sigma_r - \sigma_t)^2 - 3\tau^2} - \sigma_b \quad (4)$$

when the rotating casing is under the yield limit σ_s, axial stress σ_b, radial stress σ_r, circumferential stress σ_t and casing rotation shear stress τ, the result of Formula (4) will be the maximum bending stress allowable when the casing achieve yield limit.

3. THE RESEARCH ON THE BIGGEST BOREHOLE CURVATURE THAT ALLOWED THROUGH IN ROTATING CASING RUNNING

In the analysis of the maximum borehole curvature that casing string passes, considering respectively the following three cases, [12]: (1) The limit stress which the casing body takes place plastic deformation. The axial stress resultant that the casing suffers may exceed steel's yield limit so that the casing takes place unrecoverable plastic deformation and affect the construction. (2) The tensile strength of casing collar. The tensile strength of collar depends on the breaking strength of the tube at the end of the casing thread and the slippage strength of threaded connection. The smaller one is the tensile strength of the collar to ensure the tube at the end of collar will not be pulled out or threaded connection will not pulled off so that the casing could pass through the borehole successfully. (3) The casing threaded seal failure strength. The casing may generate threaded seal failure when the axial resultant stress at the casing collar is greater than casing threaded failure strength, affecting subsequent production operations.

3. 1. Calculate of Limit Curvature when Casing Body Buckles The bending stress of casing increases with the increase of the borehole curvature C_h. When C_h enlarge to a certain value, two point on the casing outer diameter will be the first to enter the yield (i.e. generate unrecoverable plastic deformation). The distribution of stress on the casing section is shown in Figure 3, point A or point B enter the yield, such a state of stress is called casing class I yield. There after, if the borehole curvature increases slightly, casing would take place plastic instability failure.

On the basis of Mechanics of Materials, in the case of simple bend, the computational formula is:

$$C_o = \frac{10800\sigma_a}{\pi E D_{po}} \quad (5)$$

where, E denotes steel's elasticity modulus, MPa; D_{po} is the outside diameter of casing, m; C_o is the casing curvature, (°)/30m.

Joint Formulas 4 and 5, the borehole curvature to be allowed to pass through when casing body begin buckling in the job of rotating casing running is:

$$C_c = \frac{10800 \cdot \left[\dfrac{\sigma_t + \sigma_r}{2} + \sqrt{\sigma_s^2 - \dfrac{1}{4}(\sigma_r - \sigma_t)^2 - 3\tau^2} - \sigma_b \right]}{\pi \cdot n_s \cdot E \cdot D_{po}} \quad (6)$$

where, C_c is the borehole curvature to be allowed to pass through when casing body begin buckling, (°)/30m; σ_s is the yield limit, MPa; D_{po} is the outside diameter of casing, m; n_s is the tensile safety factor, according to the design principles of API casing strength [12], n_s values of 1.8.

3. 2. Limit Curvature Calculation of Destroyed Casing Collar Under the circumstances of rotating casing running, [13, 14], the tensile strength of the casing body is higher than it of the casing collar (the threaded connecting portion) [15]. Under the action of alternating stress, tube which is at the end of the thread is easily pulled cracks. Also, the thread is easily pulled off due to accumulation of stress, and the tensile strength of tube at the end of the casing collar and the joint strength of the thread, both can be obtained from the Drilling manual (First Party), respectively to measure the tensile ability of the tube at the end of the thread. The anti-slippage capacity of the thread, which ever is smaller values as the overall tensile strength of the casing collar, donated by P_j. Meanwhile, in consideration of the influence of the stress concentration in the API specification [15], the stress concentration factor of the casing thread (the k_2 in the Formula (8) should be supposed. The ratio of P_j and the casing cross-sectional area A is the maximum allowable axial tensile stress when the thread is pulled off σ_j:

$$\sigma_j = \frac{P_j}{A} \quad (7)$$

Joint Formulas (4) and (5), and use the maximum permitted axial tensile stress at the thread σ_j instead of yield limit stress σ_s, then obtain the borehole curvature to be allowed to pass through when the casing collar begins to become failure:

$$C_m = \frac{10800 \cdot \left[\frac{\sigma_r + \sigma_t}{2} + \sqrt{\sigma_j^2 - \frac{1}{4}(\sigma_r - \sigma_t)^2 - 3\tau^2} - \sigma_b \right]}{\pi \cdot k_1 \cdot k_2 \cdot E \cdot D_{po}} \quad (8)$$

where, C_m is the borehole curvature to be allowed to pass through when the casing collar begins to become failure, (°)/30m; D_{po} is the outside diameter of casing, m; k_1 is the tensile safety factor, according to the design principles of API casing strength, $k_1$values of 1.8. k_2 is the stress concentration factor of the rotating casing thread, according to the Drilling manual, k_2 values of 1.5.

3. 3. Calculate of Limit Curvature when Casing Thread Seal Failure

For API thread standards, [16-18], its seal property mainly through mutual meshed of interference fit between in-and-out thread of contact pressure to obtain [19, 20]. Due to its structural design, there is a certain gap between the tooth threads, and the gap becomes a potential leak path. Tensile load has significant influence on the thread sealing, under axial load, axial stress on thread increases, the circumferential stress decreases, when the axial load increase to a constant value, the external thread connector radial shrinkage will occur, the screw thread gap increases, the leakage resistance decreased, thus affecting the sealing of thread. The force of casing thread leakage resistance [15] features the leak-resistant ability of threads.

The force of casing thread leakage resistance in API standards is:

$$P = ETNp(W^2 - E_s^2) / 2E_s W^2 \quad (9)$$

where, P is anti-leakage internal pressure, MPa; E is elastic modulus, MPa; T is the taper of thread; N is the number of thread turns; P is the highest point of the thread, m; W is connection diameter, m; E_s is maximum diameter for sealing section, m.

According to the force of casing thread leakage resistance, the maximum axial tension force when casing thread leakage occurs is:

$$P_{jb} = P\frac{\pi D_i^2}{4} \quad (10)$$

where, P_{jb} is the maximum axial tension force when casing thread leakage occurs, MPa; P is anti-leakage internal pressure, MPa; D_i is inside diameter of casing pipe, m;

The ratio of P_{jb} and the casing cross-sectional area A is the maximum allowable axial tensile stress when the casing thread seal failure σ_{jb}:

$$\sigma_{jb} = \frac{P_{jb}}{A} \quad (11)$$

Joint Formulas 4 and 5, and use the maximum allowable axial tensile stress when the casing thread seal failure σ_{jb} instead of yield limit stress σ_s, then obtain the borehole curvature to be allowed to pass through when the casing thread begins to seal failure:

$$C_k = \frac{10800 \cdot \left[\frac{\sigma_r + \sigma_t}{2} + \sqrt{\sigma_{jb}^2 - \frac{1}{4}(\sigma_r - \sigma_t)^2 - 3\tau^2} - \sigma_b \right]}{\pi \cdot a \cdot E \cdot D_{po}} \quad (12)$$

where, C_k is the borehole curvature to be allowed to pass through when the casing thread begins to seal failure, (°)/30m; D_{po} is the outside diameter of casing, m; a is the casing thread seal assurance factor, according to the Drilling manual, k_2 values of 1.5.

3. 4. Optimization Calculation of the Ultimate Curvature

In the process of casing running, at the maximum curvature of well, plastic deformation or tube body at the end of collar thread is pulled cut, thread connection is pulled off and thread seal failure by pulling one or several failure conditions may occur in the casing running that can not be restored. Therefore, many considerations of the possibility failures should be consider when design casing running safety. The steps of optimization calculation are:

a. Depending on the casing type selected, check basic parameters of the casing;
b. Calculation of casing stress, including axial stress, shear stress, internal pressure stress, collapse pressure and the maximum axial tensile stress whenthe casing damage;
c. Putting the above stresses in (6), (8) and (12), obtained three critical borehole curvature (i.e. C_c、C_m and C_k) when the casing will be destroyed;
d. Comparingthe C_c、C_m and C_k, the minimum of them is the biggest boreholecurvature that allowed through for the rotating casing, write for C, then $C=\min\{ C_c , C_m , C_k \}$.

4. EXAMPLESANDDISCUSSION

For example: Fetch the well trajectory data of Simulated well. The borehole trajectory parameters are shown in Table 1. The density of drilling fluid is 1.4g per cubic cm derived from the field. The casing in four open operation (the steel grade is P-110, thickness of pipe is 7.72mm) outer diameter is 139.7mm, depth of setting is 8000 meters. Checking API specification and get the figures: the elastic modulus of casing string is 209×10^3MPa, the minimum yield limit (σs) is 401.62MPa, the allowed maximaxial tension(σ_j) when thread connection slipping off is 533.78MPa, the allowed maximaxial tension (σ_{jb}) when thread leak is 605.09MPa. In order to show the effect on biggest borehole curvature that allowed through for the casing the influences of different axial forces, casing rotating and rotation speed are calculated.

(1) The axial load is zero

1) The casing is not rotating. In this instance, putting the relevant data into the Formula (6), we obtain the calculation C_c which is 26.27º/30m; putting the relevant data into the Formula (8), we obtain the calculation C_m 23.27º/30m; putting the relevant data into the Formula (12), we obtain that the calculation C_k is 23.74º/30m. According the formula C=min{C_c, C_m, C_k}, we know the biggest borehole curvature that casing string run through is 22.56º/30m.

2) The rotational speed of casing is 15 revolutions per minute. The speed of running string is 0.4 meters per second. We know that the shear stress of rotating casing is 30MPa after calculating. In this instance, putting the relevant data into the Formula (6), we obtain the calculation C_c which is 25.88º/30m; putting the relevant data into the Formula (8), we obtain that the calculation C_m is 23.16º/30m; putting the relevant data into the Formula (12), we obtain that the calculation C_k is 23.54º/30m. According the formula C=min{C_c, C_m, C_k}, we know the biggest borehole curvature that casing string run through is 22.44º/30m.

3) The rotational speed of casing is 20 revolutions per minute. The speed of running string is 0.4 meters per second. We know that the shear stress of rotating casing is 41MPa after calculating. In this instance, putting the relevant data into the Formula (6), we obtain that the calculation C_c is 25.76º/30m; putting the relevant data into the Formula (8), we obtain that the calculation C_m is 23.07º/30m; putting therelevant data into the Formula (12), we obtain that the calculation C_k is 23.34º/30 m. According the formula C=min {C_c, C_m, C_k}, we know that the biggest borehole curvature that casing string run through is 22.35º/30m.

(2) In kick-off section, taking well depth 500 meters into account. We know that the axial load of casing is 313kN (the effective axial stress σ_m is 190MPa) after calculating.

1) The casing is not rotating. In this instance, putting the relevant data into the Formula (6), we obtain that the calculation C_c is 13.84º/30m; putting the relevant data into the Formula (8), we obtain that the calculation C_m is 14.89º/30m; putting the relevant data intothe Formula (12), we obtain that the calculation C_k is 16.56º/30m. According the formula C=min{C_c, C_m, C_k}, we know the biggest borehole curvature that casing string run through is 12.42º/30m.

2) The rotational speed of casing is 15 revolutions per minute. The speed of running string is 0.4 meters per second. We know that the shear stress of rotating casing is 60MPa after calculating. The outside casing load and inside are counter balance. In this instance, putting the relevant data into the Formula (6), we obtain that the calculation C_c is 12.94º/30m; putting the relevant data into the Formula (8), we obtain that the calculation C_m is 14.55º/30m; putting the relevant data into the Formula (12), we obtain that the calculation C_k is 15.89º/30m. According the formula C=min{C_c, C_m, C_k}, we know the biggest borehole curvature that casing string run through is 11.47º/30m.

3) The rotational speed of casing is 20 revolutions per minute. The speed of running string is 0.4 meters per second. We know that the shear stress of rotating casing is 73MPa after calculating. In this instance, putting the relevant data into the Formula (6), we obtain that the calculation C_c is 12.50º/30m; putting the relevant data into the Formula (8), we obtain that the calculation C_m is 14.34º/30m; putting the relevant data into the Formula (12), we obtain that the calculation C_k is 15.90º/30m. According the formula C=min{C_c, C_m, C_k}, we know the biggest borehole curvature that casing string run through is 10.96º/30m. From the above calculation we can get a table. By analyzing the Table 2, we can summarize as follows: Under the same condition, the biggest borehole curvature that casing string run through in rotating condition is less than not rotating. The shear stress of rotating casing has agreat influence on the biggest borehole curvature that casing string run through, the higher the shear stress is, the smaller the maximum bending stress when casing reaches ultimate curvature and the biggest borehole curvature that casing string run through will be.

TABLE 1. The borehole trajectory parameters

Depth /m	Deviation /°	Azimuth /°	Vertical Depth /m	Horizontal /m	North-South /m	East-West /m
0	0	0	0	0	0	0
300	0	90	300	0	0	0
700	20	90	691.93	69.11	0	69.11
2662.87	75	90	2186.94	1233.26	0	1233.26
6945.54	75	90	3295.38	5370	0	5370
6945.76	75	90	3295.44	5370.21	0	5370.21
7278.97	91.66	90	3334	5700	0	5700
8009.39	91.66	90	3305	6700	0	6700

TABLE 2. The calculations ofborehole curvature

Axial stress /MP	Rotation speed /(r/min)	Shear stress /MP	Borehole curvature (°/30m)	The biggest borehole curvature (°/30m)
0	0	0	C_c=26.27 C_m=23.27 C_k=23.74	23.27
	15	30	C_c=25.88 C_m=23.16 C_k=23.54	23.16
	20	41	C_c=25.76 C_m=23.07 C_k=23.34	23.07
190	0	0	C_c=13.84 C_m=14.89 C_k=16.56	13.84
	15	60	C_c=12.94 C_m=14.55 C_k=15.89	12.94
	20	73	C_c=12.50 C_m=14.32 C_k=15.90	12.50

So, analyzing the shear stress in rotating condition and confirming the biggest borehole curvature that casing string run through could guide the development of casing design and construction about highly-deviated well running casing in rotating condition.

5. CONCLUSION

(1) On the basis of the bending deformation theory and the strength theory in mechanics of materials, maximum stress model of infinitesimal well casing during rotating casing was built by analysis forces acting on casing under the condition of rotating casing.

(2) The engineering calculation method of maximum borehole curvature has been proposed when the flexion deformity of the casing body or the strength fracture of the collar point or the seal failure of the thread happened under the condition of rotating casing. Any probable destruction was considered when calculate borehole curvature casing running through safety, and then get the optimization calculation method of the biggest borehole curvature that allowed through for the rotating casing.

(3) There is share stress exists when casing under the condition of rotating, so the biggest borehole curvature that casing string run through in rotating condition is less than not rotating. Analysis demonstrated that with the rotational speed of casing increase, the shear stress increases, but the biggest borehole curvature that casing string run through will decreases. The results of this research have great guiding significance on the rotating casing implemented smoothly and the design of the biggest borehole curvature that allowed through in the highly-deviated well.

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Tap Sealed

چکید

با توسعه فناوری های حفاری چاه ، فن آوری حفاری پوششی چرخشی توجه بیشتری را جلب کرده است. روش پوشش چرخشی می تواند به بهبود راندمان جابه جایی خمیر سیمان، و سپس بالا بردن کیفیت حفاری چاه کمک کند. در بخش چسبیدن، پوشش چرخشی می تواند چاه را به اجرای پی در پی پوشش وادار سازد. پوشش، تنش برشی در چرخش، تنش محوری، تنش خم شدن، استرس محیطی و استرس شعاعی را که توسط استرس فشار پوشش داخل و خارج تولید می شود، تحمل می کند. این نیروها آن را پیچیده تر میکند وقتی که حداکثر انحنا را در شرایط چرخش محاسبه می کند نه بدون چرخش. مقاله، با تجزیه و تحلیل تنشهای پوشش در شرایط چرخش، یک مدل استرس از بینهایت پوشش کوچک برای پوشش چرخشی فرض می کند. آن روش محاسبه برای حداکثر حدس مجاز برای انحنا در تغییر شکل پوشش است و یا وقتی که کوپلینگ پوشش و مهر تحت شرایط چرخش شکست می خورد. آن همچنین بزرگترین انحنای که اجازه داده می شود را به عنوان پایه ای برای طراحی و ساخت پوشش چاه تعیین می کند.

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