The ability of triangular prism drill collar BHA to prevent and correct deviation in drilling

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Abstract
A new bottom hole assembly (BHA) with a triangular prism drill collar and a flexible joint was developed to enhance the BHA’s ability of deviation prevention and correction in drilling. The deformation of the conventional BHA and the triangular prism drill collar BHA under working loads were simulated by finite element method. The result showed that the ability of the triangular prism drill collar BHA to prevent deviation in vertical well was superior to that of the conventional BHA and the triangular prism drill collar BHA had some certain ability to correct deviation in deviated well. The flexible joint length had an effect on the performance of the triangular prism drill collar BHA: when the length of the flexible joint was less than 6 m, the shorter the flexible joint length, the better the deviation prevention ability in vertical well, when the length of the flexible joint was within the range of 9–12 m, the longer the flexible joint length, the better the deviation correction ability in deviated well. Different kinds of BHAs were used in single well and adjacent well for field contrast test. The result showed that in anti-deflection fast drilling, the triangular prism drill collar BHA had excellent deviation prevention ability and it was helpful to get straight and smooth well track.

Keywords
BHA, triangular prism, drill collar, finite element method, deviation control

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Introduction
Well deviation is a challenging problem commonly existing in drilling. It seriously restricts the exploration and development of oil and gas, especially in high steep structures and high dip formation. Therefore, deviation prevention and correction, deviation control and faster drilling are problems which need to be solved urgently in drilling engineering. Using appropriate BHA with excellent ability of deviation prevention and correction is an important measure to control deviation. Packed hole assembly and pendulum assembly are widely used in drilling for deviation control. Packed hole assembly has the ability of deviation prevention, but its ability of deviation correction is poor, while pendulum assembly has excellent ability of deviation correction, but its ability of deviation prevention is poor.

Generally, in drilling, the packed hole assembly is firstly used in small deviation angle formation with high drilling speed under high weight on bit (WOB), and then the packed hole assembly is replaced by a pendulum assembly to correct the deviation with low drilling speed under low WOB when the deviation increases to a certain value. However, there exist two major problems, one is that the operation of tripping is difficult and even causes downhole accident in the replacement.
of the packed hole assembly, because the stabilizers fitted on the packed hole assembly with the diameter close to the borehole hinder the axial movement of the BHA in the wellbore. The second is that the drilling efficiency is decreased using the pendulum assembly, because the pendulum assembly performs well in deviation correction just under low WOB.7

The pre-bending BHA uses the pre-bending structure to guide the deformation of the BHA, which can produce large dynamic declivity force. For high, steep and inclined formations, its effect of deviation prevention and fast drilling is remarkable. However, it is still a difficult problem to quantitatively evaluate the dynamic characteristics of pre-bending BHA.8,9 The automatic vertical drilling tool10 and the rotary steering system11 adopt the downhole closed loop electronic control system to control the well deviation, with high control accuracy and strong drilling capability, but the system is complex and costly.

In view of these problems of the BHA for deviation prevention and correction in drilling, the triangular prism drill collar BHA which combines the advantage of packed hole assembly in deviation prevention and the advantage of the pendulum assembly in deviation correction was developed. In the vertical well section, the triangular prism drill collar BHA can stabilize the deviation angle for deviation prevention due to the triangular prism drill collar with high rigidity. In the deviation well section, the triangular prism drill collar BHA can produce lateral force and bit angle for deviation correction due to the flexible joint producing pendulum force. The rationale of the deviation prevention and correction of the triangular prism drill collar BHA was analyzed using the finite element method, and its excellent ability of deviation prevention and correction was verified by field test.

### Structure of the BHA

The triangular prism drill collar BHA was composed of five parts: the drill bit, the triangular prism drill collar, the flexible joint, the stabilizer, and the upper drill collar. The triangular prism drill collar BHA was designed according to the 8.5 inch well hole. Its structure and dimension was: \( \Phi 215.9 \text{ mm drill bit} + \Phi 214 \text{ mm triangular prism drill collar}, 9 \text{ m} + \Phi 155.8 \text{ mm flexible joint}, 6 \text{ m} + \Phi 214 \text{ mm stabilizer} + \Phi 158.8 \text{ mm upper drill collar} \). In order to contrast analyze, a pendulum assembly applied to the 8.5 inch well hole was designed. Its structure and dimension was: \( \Phi 215.9 \text{ mm drill bit} + \Phi 158.8 \text{ mm flexible joint}, 18 \text{ m} + \Phi 214 \text{ mm stabilizer} + \Phi 158.8 \text{ mm upper drill collar} \). The sketches of the two BHAs were shown in Figure 1.

The essential characteristic of the triangular prism drill collar BHA was that the high rigidity triangular prism drill collar with the diameter close to the well hole was used as the lower drill collar near the drill bit, as shown in Figure 1(a).

The distinction between the triangular prism drill collar and the ordinary drill collar was that the cross-section of the triangular prism drill collar was a triangular prism, while the cross-section of the ordinary drill collar was circular, as shown in Figure 1(c) and (d).

The rotation drag of the triangular prism drill collar BHA was smaller, because the contact area between the triangular prism drill collar and the mud cake on the wellbore was smaller than that of the conventional drill collar. The prism drill collar BHA can reduce the sticking risk by scraping the mud cake more effectively. The flow area between the prism drill collar and the wellbore annular was larger due to the cross-section shape of the triangular prism, so that the diameter of the triangular prism collar can be closed to that of the

![Figure 1. The sketches of the two BHAs: (a) triangular prism drill collar BHA, (b) pendulum assembly, (c) triangular prism drill collar cross-section, and (d) common drill collar cross-section.](image)
wellbore to increase the rigidity of the triangular prism collar BHA. The prism drill collar BHA stabilized the drill bit more effectively under high WOB to prevent deviation because higher rigidity has greater resistance to bending.

The other characteristic of the triangular prism drill collar BHA was the flexible joint fitted between the triangular prism drill collar and the stabilizer. The flexible joint can bend under the WOB, when the upper portion of BHA was supported on the wellbore by the stabilizer, as a result the triangular prism drill collar BHA can produce bit angle and lateral force for deviation correction.

**Force analysis and finite element model**

According to the vertical and horizontal bending beam column theory, the drill bit was simplified to a fixed hinge A, the drill collar was simplified to a beam, the stabilizer was simplified to sliding hinge B, the upper drill collar tangented to the wellbore on the tangent point C, the force condition of BHA was shown in Figure 2.

The upper drill collar was subjected to the axial force $F_{ax}$ by the drill string above the tangent point C. The stabilizer was subjected to the support force $F_{by}$ by the wellbore and the bending moment $M_b$ by the drill string. Drill bit was subjected to the support force $F_{ay}$ by the well bottom. The whole BHA was subjected to the longitudinal force $q \cos \alpha$ and the transverse force $q \sin \alpha$ by the gravity of the BHA, $\alpha$ was the deviation angle.

According to the force condition of BHA, the finite element model was established. The assumptions for modeling were as follows: (1) The BHA only generated small elastic deformation, and the wellbore was simplified as a rigid body; (2) The influence of the drill string above the tangent point on the deformation of BHA was ignored; (3) The tangent point located on the lower side of the deviated wellbore wall; (4) The deformation of BHA was considered only in XY plane; (5) The rotation and vibration of drilling string was not considered.

Considering the interaction between the drill string and wellbore wall, selecting the beam element 188 for the drill string, the contact finite element model between the BHA and wellbore wall was established to analyze the deformation of BHA, as shown in Figure 3. The structural balance equation of the drill string is: $[K] \{\delta\} = \{R\}$. $\{\delta\}$ is the node displacement array of the whole structure, $\{R\}$ is the node load array, $[K]$ is the global stiffness matrix. The elastic modulus of the drilling tool was 206 GPa, the Poisson ratio was 0.3, the density was 7.9 g/cm$^3$. The density of drilling fluid was 1.1 g/cm$^3$. The friction coefficient between the drilling tool and the borehole wall was 0.1. The wellbore wall was set to a rigid body.
The contact between the outer surface of the drill tool and the inner surface of the wellbore wall was created by the contact elements. The displacement of the drill bit was constrained, only the Z axis rotation freedom was not constrained. The displacements of the wellbore wall elements were constrained. The axial force contributing to the weight on the bit was loaded on the upper drill collar. Through iterative calculation, the position of the tangent point was determined, and the determined condition of the iterative calculation was that the rotation angle of the upper drill collar section located on the tangent point was zero.

**Results and analysis**

**The ability of the BHA to prevent deviation in the vertical well**

The deformation of the drilling assembly under 100 kN was shown in Figure 4. Line I was the axis of the wellbore. Line II was the shape of the drilling assembly, the arrow diagram and the cloud image were shown as the lateral displacement of the drilling assembly. The maximum lateral displacements of the two kinds of BHA both were 28.56 mm located on the tangent point. It showed that the upper drill collar contacted the borehole wall at the tangent point. Through the detailed views, the lateral displacement of the stabilizers on the two kinds of BHA was 0.95 mm. It showed that the stabilizers just contacted with the borehole wall, playing the role of lateral support to the BHA on the borehole wall. The bending deformation of the triangular prism drill collar BHA was smaller than that of the pendulum assembly. It suggested that the triangular prism drill collar BHA had better deviation prevention performance in the vertical well with higher rigidity and not easily bended under 100 kN WOB.

The lateral forces and the bit deflection angle were the major factors to analyze and evaluate the deviation prevention and correction performance of BHA. The greater the lateral force of the drill bit or the larger the deflection angle of bit, the stronger the tendency of the BHA to deviate from the drilling direction. If the deflection angle of the bit was positive, the BHA has the tendency to increase the deviation; while the deflection angle of the bit is negative, the BHA has the tendency to decrease the deviation. The tangent point location, the lateral force, and bit deflection angle of the triangular prism drill collar BHA and the pendulum assembly under 100 kN were shown in Table 1.

![Figure 4. The deformation of drilling tool assembly in vertical well: (a) triangular prism drill collar BHA and (b) pendulum assembly.](image)

[Table 1](#table1)
The tangent point location of the triangular prism drill collar BHA was higher than that of the pendulum assembly mainly because of the smaller deformation of the triangular prism drill collar BHA. The bit deflection angles of both the BHAs are positive. This suggested that both the BHAs had the tendency to increase deviation. However, the lateral forces of both the BHAs were very small, which suggested that the increasing deviation rate was low. The bit deflection angle and the lateral force of the triangular prism drill collar BHA were smaller than that of the pendulum assembly, which suggested that the increasing deviation rate of the triangular prism drill collar BHA was lower than that of the pendulum assembly, therefore the triangular prism drill collar BHA had better deviation prevention performance in the vertical well.

The ability of the BHA to correct deviation in deviated well

The deformation of the two drilling assemblies under 100 kN in the deviated well with 3° deviation angle was shown in Figure 5. The shape of the BHA was “S” in the deviated well while the shape was “C” in the vertical well because of the effect of the gravity component load. The deformation of the BHA had an impact on the lateral forces and the bit deflection angle. The deformation of the triangular prism drill collar BHA was smaller than that of the pendulum assembly.

The tangent point location, the lateral forces, and bit deflection angle of the two drilling assemblies under 100 kN in the deviated well with deviation angle of 3° was shown in Table 2.

Table 1. Tangent point location, lateral force, deflection angle of bit of BHAs in vertical well.

| Types of BHA                          | Tangent point location/m | The lateral force/N | Deflection angle of bit/° |
|---------------------------------------|--------------------------|---------------------|--------------------------|
| triangular prism drill collar BHA     | 34.96                    | 38.76               | 2.82 × 10⁻²              |
| pendulum assembly                      | 28.88                    | 70.52               | 7.21 × 10⁻¹              |

Figure 5. The deformation of drilling assembly in deviated well with deviation angle of 3°: (a) Triangular prism drill collar BHA and (b) pendulum assembly.
The tangent point location of BHA had influence on the lateral force. The higher the tangent point location, the bigger the lateral force. The lateral force of BHA in the deviated well was helpful for the deviation correction. The tangent point location of the triangular prism drill collar BHA was slightly higher than that of the pendulum assembly. The lateral force of the triangular prism drill collar BHA was larger than that of the pendulum assembly. One reason was the weight of the triangular prism drill collar BHA was larger, and another reason was that the tangent point location of the triangular prism drill collar BHA was higher. It suggested that the two BHAs had the ability of deviation correction and the deviation correction ability of the triangular prism drill collar BHA was better than that of the pendulum assembly in respect of the lateral force.

The bit deflection angle of the two BHAs was negative, which suggests that the two BHAs had the tendency to decrease deviation. The bit deflection angle of the pendulum assembly was larger than that of the triangular prism drill collar BHA, which suggests that the pendulum assembly had stronger deviation correction ability with the same lateral force. The triangular prism drill collar BHA has deviation correction ability with negative bit deflection angle, mainly due to the flexible joint which can produce large bending deformation under high WOB.

The effect of the flexible joint on the deviation prevention and correction

The length of the flexible joint in triangular prism drill collar BHA had great influence on the deviation prevention and correction. The lateral forces and bit deflection angles of the triangular prism drill collar BHA with different length of flexible joint under 100 kN WOB were shown in Figure 6.

In the vertical well, when the length of the flexible joint was less than 6 m, the lateral force and bit deflection angle of the triangular prism drill collar BHA was positive, which suggest that the BHA had the effect of increasing deviation. The lateral force decreased with the increase of the length. The Bit deflection angle increased with the increase of the length. In the vertical well, the lateral forces were very small so that it had little effect on the deviation and the deviation mainly induced by the bit deflection angle. Therefore, in the vertical well, when the length of the flexible joint was less than 6 m, the shorter the length of the flexible joint, the more effective the triangular prism drill collar BHA for deviation prevention. When the length of the flexible joint was greater than 9 m, the lateral force and bit deflection angle of the triangular prism drill collar BHA were negative, which suggested that the BHA had decreasing deviation effect in the deviated well, while it had an increasing deviation effect.

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**Table 2.** Tangent point location, lateral forces, deflection angle of bit of BHA in deviated well.

| Types of BHA                      | Tangent point location/m | The lateral force/N | deflection angle of bit/° |
|----------------------------------|--------------------------|---------------------|---------------------------|
| triangular prism drill collar BHA | 29.22                    | -321.44             | -8.54 × 10⁻²             |
| pendulum assembly                | 27.51                    | -253.49             | -2.69 × 10⁻¹             |

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**Figure 6.** The effect of the flexible joint length on the lateral force and bit deflection angle: (a) in vertical well and (b) in deviated well with deviation angle of 3°.
in the vertical well. Therefore, with the longer flexible joint, the ability of the deviation prevention of the triangular prism drill collar BHA was worse.

In the deviated well with deviation angle of 3°, when the length of the flexible joint was less than 9 m, the lateral force and bit deflection angle of the triangular prism drill collar BHA were negative which suggested that the BHA had decreasing deviation effect. Furthermore, its absolute value increased with the increase of the length of the flexible joint, which suggested that the longer the length of the flexible joint, the better the ability of deviation correction of the triangular prism drill collar BHA, in the deviated well. When the length of the flexible joint was 12 m, the absolute value of lateral force and bit deflection angle decreased, which suggests that there was a critical value of the flexible joint length for the ability of deviation correction of the triangular prism drill collar BHA. In the range of critical value, increasing the length of the flexible joint can help to improve the ability of deviation correction.

**Field test**

**Contrast test in single well**

To verify the deviation prevention and correction ability of BHA, the triangular prism drill collar BHA and the pendulum assembly were used in an oil well with high-angle structure in Sichuan and Chongqing region of China for contrast test. The depth of the test well interval was 528–1090 m, the hole diameter was 215.9 mm. The structure and dimension of the triangular prism drill collar BHA in the test was: Ø215.9 mm drill bit + Ø214 mm triangular prism drill collar, 9 m + Ø155.8 mm flexible joint, 6 m + Ø214 mm stabilizer + Ø158.8 mm upper drill collar. The structure and dimension of the pendulum assembly was: Ø215.9 mm drill bit + Ø158.8 mm flexible joint, 18 m + Ø214 mm stabilizer + Ø158.8 mm upper drill collar. The triangular prism drill collar was showed in Figure 7.

The result of the comparative test was shown in Figure 8. The well interval of 528–937 m drilled by the triangular prism drill collar BHA. The angle of deviation increased from 3.68° at 528 m to 4.42° at 907 m, the build up rate was 0.11°/100 m. The angle of deviation decreased to 4.04° at 937 m, the drop off rate was 1.27°/100 m. The well interval of 937–1085 m drilled by the pendulum assembly. The angle of deviation decreased from 4.04° to 2.59°, the drop off rate was 0.98°/100 m. The test result showed that the triangular prism drill collar BHA had excellent deviation prevention ability and had some certain ability to correct deviation. In the test, the drilling speed of the triangular prism drill collar BHA was 3.49 m/h, while the drilling speed of the pendulum assembly was 2.19 m/h, which suggested that the triangular prism drill collar BHA had the advantage in anti-deflection fast drilling.

**Contrast test in adjacent well**

The triangular prism drill collar BHA and the conventional BHA were used in three adjacent oil wells with high-angle structure in Sichuan and Chongqing region of China for contrast test, and the result of the test was shown in Figure 9. The angle of deviation of the oil well used the triangular prism drill collar BHA increased from 2.02° at 428 m to 2.48° at 700 m, the build up rate only was 0.17°/100 m, while the build up rate of the adjacent wells 1# and 2# used the conventional BHA were 0.79°/100 m and 1.32°/100 m, respectively. It showed that the triangular prism drill collar BHA had excellent deviation prevention ability.
The deviation curve of the oil well used the triangular prism drill collar BHA was smooth, different from that of the adjacent well used conventional BHA with sawtooth waveform shape, which suggested that the triangular prism drill collar BHA had excellent ability of deviation prevention. The rigidity of triangular drill collar is large, and the deflection angle is small, so the angle of well deviation is very stable, and the well track is smooth. It is helpful to get a straight well track.

Conclusion
The triangular prism drill collar BHA had the ability to prevent deviation in the vertical well and some certain ability to correct the deviation in the deviated well. The triangular prism drill collar BHA can improve drilling efficiency by higher WOB while achieving the aim of deviation control.

The ability of the triangular prism drill collar BHA to prevent deviation was the result of the triangular prism drill collar with high rigidity and having strong resistance to bending deformation.

The ability of the triangular prism drill collar BHA to correct deviation was the result of the flexible joint bending deformation, which helped the drill bit to produce builddrop angle. The shorter the flexible joint, the better deviation prevention ability of the triangular prism drill collar BHA, while the increase of the length of the flexible joint appropriately can improve the deviation correction ability of the triangular prism drill collar BHA.

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