Research on the Compatibility Between Washover String and Casing in Directional Casing Damage Wells

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Abstract: Nowadays extracting or changing casing is a mature technique used in vertical wells, which can solve the problems of casing breaking and corrosion. But for directional casing damage wells, the phenomena of milling head cutting casing often happen because of the stiffness difference between washover string and casing. In order to evaluate the compatibility between washover string and casing, some studies have been made in this paper: (1) an axial force calculation model is established, which is used for mechanical analysis of washover string in the condition of well wall outside and casing inside. (2) a turning force calculation model is obtained through mechanical analysis of the milling head-ball-casing assembly. The calculation model can reflect the compatibility between washover string and casing. And on this basis the contact stress of the assembly can be simulated with Comsol Multiphysics. When the contact stress exceeds casing’s yield stress, yield failure happens. A poor compatibility will result in casing to be cut off and the interruption of extracting operation. The research results provide a method for evaluating the compatibility between washover string and casing.

1. Introduction
During extracting casing in directional wells, the problems of milling head cutting casing often arise in the wellbore curved portion because of the stiffness difference between washover string and casing. As a result, the phenomenon of fish falling happens. In order to increase the compatibility between washover string and casing, some special tools, including ball milling head, variable direction joint (VDJ) and ball centralizer are developed. There is no doubt the stress characteristics of the washover string with these tools are different with that of the regular string [1]. What the new string stress condition and applicability have been utterly unknown so far. To solve the problem, a turning force calculation model is established on the basis of pipe string mechanics theory, which can quantitatively evaluate the compatibility between washover string and casing. And the contact stress under a turning force can judge whether the casing is damage.

2. Structure of the special washover string
The special washover string is composed of ball milling head, ball centralizer, variable direction joint and milling sleeve. The structures of special washover string and tools are as shown Figure 1.
Figure 1. The structures of special washover string and tools

As shown in Figure 1, the ball milling head has 12 balls on its inner wall. The 12 balls are equally divided into two parallel rows. Each ball will turn with the milling head. So, the contact form between milling head and casing will be transformed from line type to point type, which is beneficial for decreasing the friction and protecting casing from cutting. For the variable direction joint, it contains internal and external tubes. Some keys are around the outer wall of the internal tube. And there are the same numbers of keyways distributed on the inner wall of the external tube. Some space exists between the key and keyway when the variable direction joint is at a free state. Under the effect of axial compressive force, the internal tube will be near to the external tube. And the key and keyway will mesh with each other in a range of circumferential angle. As a result, the variable direction joint generates a bending angle, which can decrease the stiffness of washover string on the one hand and increase the compatibility between washover string and casing. For the ball centralizer, there are 8 balls uniformly embedded on the inner wall. Each ball will turn with the centralizer like the milling head. As a result, a small friction between the centralizer and casing can be obtained.

3. Establishing the axial model for washover string

There are four factors that affect the axial force of washover string. Firstly, the variable direction joint can increase the deflecting capacity of washover string and create a new well trajectory in extracting casing operation. The variable direction joint will change the size and direction of axial force. Secondly, the casing can touch washover string’s inner wall and friction is generated [2-3]. The friction will become greater when casing is buckling. Thirdly, the centralizer can touch the well wall and friction is generated [4-5]. Finally, when the washover string is bore a greater axial compressive force, the tortuosity of the washover sleeve between two centralizers will increase and touch the well wall. So, new friction can be generated inevitably [6].

3.1. The deflecting capacity of washover string

The variable direction joint can change the deflecting capacity of the washover string. We take the structure of washover string in Figure 2 as example. Based on the theory of “three points determining one circle” [7-8], the deflecting capacity of washover string can be calculated.
The deflecting capacity of washover string can be obtained through analyzing the geometrical relationship between each tool in Figure 2.

\[
k = \frac{360\left[\alpha L_4 + \beta (L_3 + L_4)\right]}{\pi (L_1 + L_2 + L_3 + L_4)(L_5 + L_6 + L_4)}
\]

Where, \(k\) is the deflecting capacity of washover string, °/30 m. \(\alpha\) and \(\beta\) are the bending angles of different variable direction joint respectively, °. \(L_1, L_2, L_3, \text{and } L_4\) represent the length of different tool, m.

As described above, the washover string can create a well trajectory in extracting casing operation. The deviation angle at \(x_j\) depth can be expressed as equation (2).

\[
y_j = \begin{cases} 0; & x_j \leq L \\ \frac{360\left[\alpha L_4 + \beta (L_3 + L_4)\right]}{\pi (L_1 + L_2 + L_3 + L_4)(L_5 + L_6 + L_4)}(x_j - L); & x_j > L \end{cases}
\]

Where, \(L\) is the length of well vertical section, m. \(x_j\) is well depth, m. \(y_j\) is the deviation angle, °.

### 3.2. The axial force model of washover string

Numerical computation method is usually used for calculating pipe string mechanics. The key of it is element algorithm. The washover string is divided into \(m\) sections from well head to bottom. And each section is named \(1, 2, 3, \ldots, m+1\) respectively. For \(j\), two sections adjacent to it are \(j-1\) and \(j+1\). The axial force of \(j\) section can be obtained through equation (3)-(5).

\[
q_{\text{in},j} = q_j + \rho_{\text{in}}A_{\text{in},j} - \rho_{\text{out}}A_{\text{out},j}
\]

\[
F_{r, j+1} = F_{r, j} + q_{r, j}L_j - f_{l, j} \sum \left(N_j^i + N_j^i + N_j^i\right); \quad x_j \leq L
\]

\[
F_{r, j+1} = F_{r, j} + q_{r, j}L_j \left[\frac{360\left[\alpha L_4 + \beta (L_3 + L_4)\right]}{\pi (L_1 + L_2 + L_3 + L_4)(L_5 + L_6 + L_4)}(x_j - L)\right] - f_{l, j} \sum \left(N_j^i + N_j^i + N_j^i\right); \quad x_j > L
\]

\[
F_{r, j} = F_{r, j} - P_{\text{in},j}A_{\text{in},j} + P_{\text{out},j}A_{\text{out},j}
\]

\[
F_{r, j+1} = F_{r, j} - q_{r, j}L_j + f_{l, j} \sum \left(N_j^i + N_j^i + N_j^i\right); \quad x_j \leq L
\]

\[
F_{r, j+1} = F_{r, j} - q_{r, j}L_j \left[\frac{360\left[\alpha L_4 + \beta (L_3 + L_4)\right]}{\pi (L_1 + L_2 + L_3 + L_4)(L_5 + L_6 + L_4)}(x_j - L)\right] + f_{l, j} \sum \left(N_j^i + N_j^i + N_j^i\right); \quad x_j > L
\]

\[
F_{r, j} = F_{r, j} - P_{\text{in},j}A_{\text{in},j} + P_{\text{out},j}A_{\text{out},j}
\]
Where, \( q_j \) is the weight of 1 meter washover sleeve, N/m; \( A_{in,j} \) and \( A_{out,j} \) are the inner and outer cross-sectional area of washover sleeve, \( \text{m}^2 \); \( F_{\tau,j} \) is the equivalent axial force, N; \( f_{ij} \) is the friction coefficient between washover string and well wall, dimensionless; \( F_{\tau,j} \) is the actual axial force, N; \( N_{1j} \) is the normal pressure between washover string and casing, N; \( N_{2j} \) is the normal pressure between the centralizers and well wall, N; \( N_{3j} \) is the normal pressure between the washover string and well wall, N.

### 4. Establishing the compatibility model between washover string and casing

The ball milling head bears a turning force when extracting casing. It is a reaction force generated by casing when the milling head touches it. The turning force is influenced by the axial force of washover string, the deviation angle of casing and the deviation angle of milling head. It can reflect the compatibility between washover string and casing. When the turning force becomes greater, the casing will more easily damage. Figure 3 shows the force state of the milling head. There are three forces acted on it. One named \( F_F \) is the axial force generated by the upper washover string. Another named \( F_a \) is the turning force generated by casing. The last one \( F_b \) named is the reaction force generated by cement sheath. The relationship between three forces can be represented by equation (6).

\[
\begin{align*}
\overrightarrow{F}_t &= \overrightarrow{F}_a + (-\overrightarrow{F}_b) \\
F_{ax,j} &= F_a \sin{(y_j - y_i)} \\
F_{bx,j} &= F_a \cos{(y_j - y_i)}
\end{align*}
\]

Where, \( y_i \) represents the deviation angle of casing at \( x_j \) depth.

When substituting the equation (2) into (6), we can obtain the turning force model for the washover string structure as shown in figure 2.

\[
\begin{align*}
F_{ax,j} &= 0; \quad x_j \leq L \\
F_{ax,j} &= F_{a,j} \sin{\left( \frac{360}{\alpha L_a + \beta (L_a + L_q)} \left( x_j - L \right) - \beta \right)}; \quad x_j > L
\end{align*}
\]

We can obtain that from equation (7): (a) when the deviation angle of washover string at \( x_j \) depth is smaller than that of the casing, the turning force is negative. As a result, the ball milling head will cut the upper parts of casing. Otherwise, the ball milling head will cut the bottom parts of casing. (b) When the gap between the deviation angle of washover string and casing becomes larger, the turning force will be greater and the casing will be more easily cut.

We can build a milling head-ball-casing geometric model with Comsol Multiphysics software. Casing’s stress under a turning force can be obtained by numerical simulation. The criteria that
guarantee casing in a safe condition is as show in equation (8).

\[
\frac{F_{a,j}}{A} \leq P_{\text{yield}}
\]

(8)

Where, \( A \) is the contact area between ball milling head and casing, \( m^2 \).

5. Case study

We take a casing damage well for example. The well’s trajectory is as shown in Figure 4 (a). The casing damage point is located in 300m. And the extracting casing operation is needed. The washover string structure is milling head \( \times 0.455 \text{ m} + 1 \text{ centralizer} \times 1.014 \text{ m} + 1 \text{ VDJ (1.6°)} \times 0.95 \text{ m} + 1 \) washover tubing \( \times 10 \text{ m} + 1 \text{ VDJ (1.6°)} \times 0.95 \text{ m} + 1 \text{ centralizer} \times 1.014 \text{ m} + n \) washover sleeve. The other basic parameters are as follows: the wellbore diameter is 0.33 m. The Casing inner and outer diameters are 0.127m and 0.139m respectively. The weight of 1 meter casing is 20.83 kg/m. The casing’s yield strength is 431 MPa. The inner and outer diameters of washover sleeve are 0.2266 m and 0.2445 m respectively. The weight of 1 meter washover sleeve is 20.83 kg/m. The elasticity modulus of steel is \( 2.06 \times 10^{11} \text{ Pa} \). The density of washover fluid is 1690kg/m\(^3\). The turning force is 63.57 kN on the basis of equation (1)-(7). When establishing a milling head-ball-casing geometric model in Comsol Multiphysics as shown in Figre 5 (b), we can simulate the casing stress. The simulation result is as shown in Figure 5(c).

![Figure 4. Casing damage well trajectory and contact stress simulation](image)

We can obtain from Figure 4 that the maximum contact stress is 4400 MPa, which far exceeds the casing’s yield stress 431 MPa. And casing will generate an unrecoverable plastic deformation during extracting. As the extracting operation continues, the plastic deformation increases gradually. At last, the casing is cut by milling head and fish falling happens.

6. Conclusions

(a) Based on analyzing the effects of casing, centralizes, well wall and variable direction joint, a axial force calculation model for washover string is established. And a dedicated numerical method is used for solving the model.

(b) Based on the mechanical analysis of milling head-ball-casing assembly, a turning force model is established. It can reflect the compatibility between washover string and casing.

(c) A finite model for analyzing casing breaking is established. And the contact stress of washover tubing ball-casing combination is obtained with the numerical method. Moreover, how the casing breaks is analyzed.

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