Force Analysis of Logging Cable in Deep Well

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Abstract—With the increase of deep wells, high temperature and high pressure wells and complex wells, the demand for logging is also increasing. Wireline logging is an important technical means to obtain downhole data in the process of petroleum testing. This paper establishes a cable mechanics model by analyzing the main influencing factors of the cable force in the inclined well section or the vertical well section. Calculate the lifting power of the tool. Through logging calculation, the force change law of the downhole cable and tool string is obtained when the wellhead pressure changes.

1. Introduction

With the increasing scale of oil and gas exploration and development, the application of new materials, information transmission technology, information processing technology and cable logging technology has developed rapidly. The oil and gas service companies are committed to the research of various new technologies and have made considerable progress in cable logging technology[1][2]. At present, there is a lack of a relatively complete force analysis of downhole tool and cable in the well test operation. The cable force not only affects the normal admission of data and the safety of construction operations, but also affects the normal process of exploration and development, and increases the cost of salvage operations[3]. Therefore, it is necessary to analyze the force and strength safety of the logging cable in construction.

Existing research on the force of the tool after it is placed in the well is seldom, and most of the research focuses on the mechanical analysis of the cable and tractor in the process of entering and lifting. LOCAL E[4] described in detail the cable tension and elongation in horizontal wells with various conditions, and introduced the calculation method of the sum of cable resistance and self-weight resistance in horizontal wells. Castillo. H.C[5] applied software to mechanically model the cable, obtained the force generated by the fluid flow on the cable, and compared the cable surface tension predicted by the model with the measured value. McSpadden. A[6] implemented a mathematical model in a computer program for numerical estimation in inclined wells or vertical wells, and graphically represented the behavior of cables to predict the use of cables (wire rope or steel wire) to run and pull tools. The resistance involved in exiting a deviated well, it is concluded that the curvature of the deviated well will significantly increase the resistance and form a cumulative nonlinear resistance between the downhole tool and the surface cable.

In previous studies on the force analysis of logging cables, there is no relevant calculation method for the force problems of the cable-connected tool string during down logging in the inclined well section or vertical well section. Therefore, this article starts from the force analysis of the cable and...
the tool string in the vertical well section, and proposes the force of the cable under different wellhead pressures and the maximum pulling force of the cable under the corresponding conditions.

2. Mechanical Model

2.1. Force analysis of the micro-element section of the cable

Take out a section of cable micro-element to analyze its force. As shown in Fig.1, the force is mainly affected by gravity($G_i$), buoyancy($F_{fi}$), and the viscous resistance force caused by downhole fluid flow($F_{\lambda i}$). The micro-element section $i$ receives an upward pulling force($T_i$); the micro-element section $i$ receives a downward pulling force($T_{i+1}$).

According to the force analysis, the mechanical balance equation is established as:

$$T_i + F_{\lambda i} + F_{\beta i} = T_{i+1} + G_i$$

(1)

Among them, the cable gravity, cable buoyancy, and the viscous resistance force of the downhole fluid flow to the cable are[7]:

$$\begin{align*}
G_i &= \frac{\rho_g g s_i}{1000} \\
F_{\beta i} &= \frac{\pi \rho_g g s_i d^2}{4} \\
F_{\lambda i} &= C_f \pi ds \frac{\rho_g u_0^2}{2}
\end{align*}$$

(2)

In natural gas wells, most of the products are gas and oil coexistence, so the total oil and gas flow is used for calculation. Among them, the gas flow is the main component and the gas is compressible. A semi-empirical model is used to calculate the actual flow velocity in the gas pipe[8]. Therefore, the actual flow rate of the gas in the pipe:

$$u_0 = \frac{4Q}{3600 \times 24 \times \pi D^2 P} \left( \frac{273 + t}{273} \right)$$

(3)

The average frictional resistance coefficient $C_f$ between the cable and the downhole fluid is a coefficient related to the Reynolds number $Re(=u_0 L/\nu)$, which can be calculated by the following formula:

$$C_f \approx \frac{0.455}{(\log Re_L)^{2.58}}$$

(4)

From Equations (1) and (2), the force balance equation of the cable micro-element section $i$ can be obtained as follows:

$$T_i = T_{i+1} + \left[ \frac{\rho_g g s_i}{1000} - \frac{\pi \rho_g g d^2}{4} - C_f \pi ds \frac{\rho_g u_0^2}{2} \right] s_i$$

(5)
2.2. Force analysis of tool string in downhole

In the force analysis of the tool string, in order to simplify the calculation, the force component diagram is shown in Fig. 2. The tool string is mainly subjected to the upward pulling force of the cable ($T_n$), gravity (the weight of the tool string in the air) ($G_T$), the force produced by the fluid pressure difference ($F_{Tp}$), and the viscous resistance force generated by the downhole fluid flow ($F_{Tl}$). Therefore, the pulling force of the cable by the tool string is as follows:

$$T_n = G_T - F_{Tp} - F_{Tl}$$  \hspace{0.5cm} (6)

1) The force produced by the fluid pressure difference

As the downhole fluid flows through the tool string, the flow channel suddenly shrinks first, and then the flow channel suddenly expands, so the overcurrent pressure difference experienced by the tool string can be calculated\(^\text{[7]}\). The fluid pressure difference at the lower end of the tool string is:

$$\Delta P_d = \frac{u_1^2}{2} \left[ \rho \left( \frac{A_D}{A_{d_1}} - 1 \right)^2 + \left( 1 - \frac{(A_D - A_{d_1})^2}{A_D^2} \right) \right]$$  \hspace{0.5cm} (7)

Similarly, the fluid pressure difference at the upper end of the tool string can be obtained as

$$\Delta P_u = \frac{\rho u_1^2}{2} \left[ \left( 1 - \frac{A_D - A_{d_2}}{A_D} \right)^2 - \left( 1 - \frac{A_D^2}{(A_D - A_{d_2})^2} \right) \right]$$  \hspace{0.5cm} (8)

The fluid velocity $u_1$ in the annulus gap between the tool string and the oil well pipe can be calculated by Equation (3). From the fluid pressure difference between the upper and lower ends of the tool string, the force produced by the fluid pressure difference can be obtained as

$$F_{Tp} = \frac{(\Delta P_d + \Delta P_u) \pi d_{l}}{4}$$  \hspace{0.5cm} (9)

2) The viscous resistance force of the fluid to the tool string

The viscous resistance force of the fluid to the tool string can be approximated by the following formula\(^\text{[9]}\):

$$F_{Tl} = \frac{2 \pi u_1 d_{l} L_T}{\ln(D/d_{l})}$$  \hspace{0.5cm} (10)
2.3. Analysis of the force on the connection between the micro-element section of the cable and the tool string

The force analysis of the connection between the cable micro-element section n-1 and the tool string is shown in Fig.3. \( T_n \) is the tensile force of the tool string to the cable micro-element, and its calculation formula is shown in Equation (6). So the balance equation can be obtained as:

\[
T_{n-1} = G_T - F_{fp} - F_{fj} + \left[ \frac{\rho_g \cdot g}{1000} \frac{\pi d^2}{4} - C_f \pi d \frac{P_o u^2}{2} \right] s
\]  

Fig. 3 The force analysis diagram of the connection between the micro-element section of the cable and the tool string

2.4. Force analysis of the micro-element section of the cable at the wellhead

The main forces on the cable micro-element at the wellhead are the total tension of the lower cable and tool string \( T_1 \), the force generated by the wellhead pressure difference \( F_p \), the friction resistance of the cable winch \( F_j \), the cable tension at the end of the cable winch \( T_0 \), and the gravity of the cable micro-element section \( G_0 \). The balance equation is as follows:

\[
T_1 = F_p + F_j + T_0 + G_0
\]  

Fig. 4 The force analysis diagram of the micro-element section of the cable at the wellhead

The force generated by the wellhead pressure difference is calculated as follows:

\[
F_p = (P_{out} - P_o) \times \pi d^2
\]  

In the actual engineering calculation, the friction resistance of the cable winch is calculated as follows\(^{[10]}\):

\[
F_j = F_p \times f
\]  

2.5. Maximum tension on the cable

The analysis shows that the cable micro-element section at the winch drum receives the largest tensile force, which is determined by the total tensile force \( T_i \) of the cable and tool string at the lower end of the wellhead (excluding the counterweight that overcomes the force of the wellhead differential pressure), and the lifting friction on the cable. The calculation formula is as follows:

\[
G = T_n + \sum_{i=1}^{n} \left[ \left( \frac{\rho_g \cdot g}{1000} \frac{\pi d^2}{4} - C_f \pi d \frac{P_o u^2}{2} \right) s_i \right] - F_p \times \frac{1 + f}{g}
\]
3. Example Calculation

In order to explore the practicability of the mechanical model established in this paper, a deep natural gas well is taken as an example. By calculating the force of the cable under different wellhead pressures, and drawing the cable force diagrams under different wellhead pressure changes (Fig.5, Fig.6, Fig.7), and the maximum tensile force of the cable (Fig.8).

It can be seen from Fig.5 that the buoyancy of the cable will increase with the increase of wellhead pressure. This is due to the increase of wellhead pressure, which leads to an increase in the average density of natural gas in the well, which affects the buoyancy of the cable. However, it can be seen from Fig.6 that the viscous resistance force of natural gas to the cable decreases as the pressure increases, because the viscous resistance force is related to the flow rate. While the wellhead pressure increases, the equivalent daily gas production will decrease, and the flow rate of natural gas in the well will also decrease, resulting in a decrease in viscous resistance force. Through calculation, it can be known that the buoyancy and viscous resistance force of the cable is relatively small compared with the cable's own gravity. It can be seen from Fig.7 that the pressure differential force experienced by the wellhead cable increases linearly with the increase of the wellhead pressure. The magnitude of this differential pressure forces is caused by the pressure difference between the pressure of the natural gas at the wellhead and the external atmospheric pressure. Therefore, if the cable and tool string are to be smoothly down to the well, the tool string must be counterweighted to offset this pressure differential force.

![Fig. 5 The buoyancy of the cable changes with the wellhead pressure](image1)
![Fig. 6 The viscous resistance force of natural gas to the cable changes with the wellhead pressure](image2)

![Fig. 7 The force of the wellhead pressure difference on the cable changes with the wellhead pressure](image3)
![Fig. 8 Maximum tensile force of the cable under different wellhead pressures](image4)
4. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) Through the force analysis of the downhole cable and tool string, the force model of the downhole cable and tool string is obtained. At the same time, the calculation formula of the maximum cable tension is obtained on this basis.

(2) It can be known from the actual well calculation that this calculation method not only considers the wellhead pressure, but also considers the impact of production on the force of the cable. Therefore, in actual application, the maximum force of the cable can be calculated according to the difference of daily output and wellhead pressure, so as to achieve the purpose of protecting the safe operation of the cable and tool string in the well, which has certain guiding significance for reducing the logging risks.

Nomenclature

\[ P_s = \text{The weight of the cable per kilometer of length, kg/km}; \]
\[ \rho = \text{Density of downhole fluid in the pipe, kg/m}^3; \]
\[ d = \text{Cable micro-element diameter, m}; \]
\[ s = \text{Cable micro-element length, m}; \]
\[ Q = \text{Natural gas flow, m}^3/\text{d}; \]
\[ D_i = \text{Inner diameter of oil well pipe, m}; \]
\[ P = \text{Average pressure in oil well pipe, MPa}; \]
\[ t = \text{Average temperature in oil well pipe, °C}; \]
\[ \nu = \text{Dynamic viscosity of fluid in oil well pipe, Pa⋅s}; \]
\[ L = \text{The length of the cable into the well, m}; \]
\[ A_{i/d} = \text{Internal cross-sectional area of oil well pipe, m}^2; \]
\[ A_d = \text{Cross-sectional area of tool string, m}^2; \]
\[ d_T = \text{The diameter of the tool string, m}; \]
\[ L_T = \text{The length of the tool string, m}; \]
\[ P_{\text{out}} = \text{Wellhead fluid pressure, Pa}; \]
\[ P_0 = \text{Standard atmospheric pressure, Pa}; \]
\[ f = \text{The coefficient of friction between the cable and the winch is generally 0.1 to 0.2}. \]

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