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Tripping Friction Model for Multi-Stage Fracturing and Completion String in Horizontal Well

HU Chaoyang[a]; AI Chi[a],*; WANG Fengjiao[a]; LI Yuwei[a]; FENG Fuping[a]

[a] Northeast Petroleum University, Daqing, China.
* Corresponding author.

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Abstract

The structure of multi-stage fracturing completion string in horizontal well is complicated. The downhole tools such as packers and sliding sleeves whose dimensions are very close to the size of the borehole, and the completion string has strong stiffness as well. Thus, it leads to larger frictional restriction when running string. Based on the above reasons, it is essential to calculate the tripping capacity before the strings running into the well in case of sticking off. However, calculation errors of conventional string tripping models are relatively larger. This paper took the structure of multi-stage fracturing completion string into consideration, divided completion string by contact points between string and borehole to establish the stress and bending model of the string between two contact points, and established the tripping friction and hookload model for multi-stage fracturing completion string. An applied example of multi-stage fracturing horizontal well in Hong 90-1 block of Jilin Oil Field shows that the created model in the paper is more accurate. The accuracy of hookload while the string running in form curved section to bottom is 95.80%. The established model is more accurate and reliable. It can be used to estimate the tripping ability of the multi-stage fracturing completion string.

Key words: Multistage fracturing; Tripping; Tripping friction; Mechanical model

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INTRODUCTION

The multi-stage fracturing of horizontal wells is an important technology to improve the shale gas, tight reservoir, tight gas reservoir production, and is widely used in many oil and gas field development[1-3]. In order to reduce the construction time of multistage fracturing horizontal well, a technology that using completion string as the fracturing string to perform multi-stage fracturing was proposed. This technology directly implementing multistage fracturing in open hole section or after perforation section. It not only can save lots of time and cost, but also can reduce the reservoir pollution, and improve the productivity of oil and gas well[4-6]. Completion string for multistage fracturing horizontal well includes packer, sliding sleeve and so on, but the outside diameter of these tools is similar to size of the hole and rigidity is strong. If the fracturing series design too much, it may cause the running friction resistance of string too large. Once stuck, it will account for a serious problem[7-8].

However, string for multistage fracturing horizontal well includes downhole tools such as packers, sliding sleeve have big diameter, high rigidity, and the friction of the rigid generated can not be ignored, so the conventional string model is different from multi-stage fracturing and completing string in string structure and mechanics. Therefore it should establish applicable calculation model to the special structure for completion string of multi-stage fracturing horizontal wells.

1. STRUCTURE OF MULTI-STAGE FRACTURING AND COMPLETION STRING

Multi-stage fracturing and completion string is a complex of conventional fracturing string and completion string. The string contains completion and fracturing string of multi-stage fracturing well, including sliding sleeves, packers, anchors and other fracturing tools[9]. Structure of multistage fracturing completion string as is shown in Figure 1.

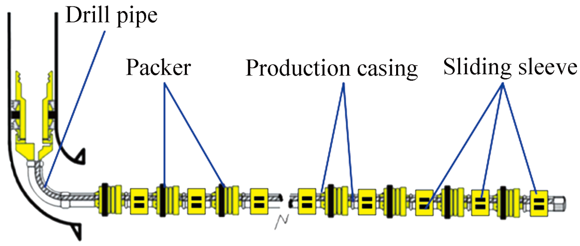

Figure 1
Structure of Multi-Stage Fracturing Completion String

Production casing is the main section of the string, floating shoe being at the string most front end, and is used to guide the string tripping in wellbore. The number of packers and sliding sleeves depend on the number of fracturing stage. One sliding sleeve was opened in each fracturing stage, and the packers near the opening sleeve assure the stage of fracturing. Hanger is located in the upper of casing, and the lower is the completion casing and downhole tools of multi-stage fracturing, and the upper is the drill pipes that make multi-stage fracturing completion string into the bottom. After fracturing, hanger detached to the drill pipe, hanging on the technical casing with the lower part of the string.

2. THE CALCULATION MODEL OF RUNNING FRICTION OF MULTI-STAGE FRACTURING STRING

There are many contact points between string and sidewall. In order to calculate the stress of multiple hinge bearing rod and deformation of bending, string is divided into multiple sections according to the contact point, obtained the string bending model between two contact points, and then establish the mechanical model of entire string stress. Combined with the new contact points between string and borehole wall, finally we established the calculation model of friction in casing string of multi-stage fracturing string and wellhead hook load.

2.1 The Sting Bending Model Between Two Contact Points

String is divided into n sections according to the contact point, assuming two points D_i, D_{i+1} are two connection points of the string section i. In the two-dimensional well bore trajectory, it makes line connecting between two contact points as x axis established coordinate system as is shown in Figure 2.

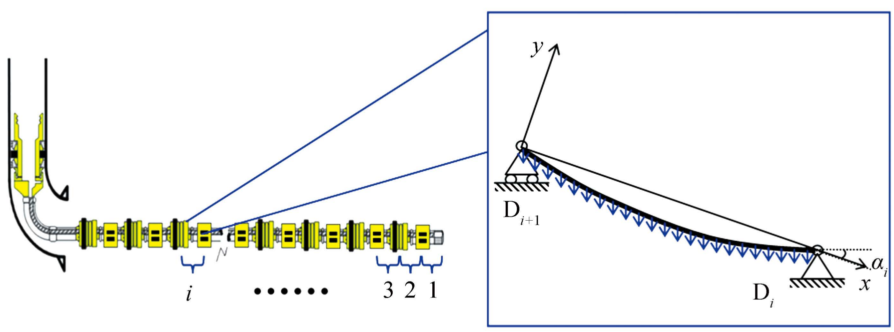

Figure 2
The String Bending Model Between Two Contact Points

Moment equilibrium equation of y axis is as follows:

$$\begin{aligned} M(x) = & -0.5q_i\cos\alpha_i x^2 + (0.5lq_i\cos\alpha_i + M_{1i}/l - M_{2i}/l)x \\ & -0.5q_i(\sin\alpha_i)xy_i - P_{2xi}y_i + M_{2i} \end{aligned} \tag{1}$$

where y_i is string deflection along with y direction generated from point D_{i+1} to x axis on string, m; α_i is included angle between x axis and horizontal plane; P_{2xi} is supporting force of point D_{i+1} in x direction, N; M_{1i} is the shaft torque on point D_i, N·m; M_{2i} is the shaft torque on point D_{i+1}, N·m; q_i is string linear density in drill fluid, N/m; l is the string distance between point D_i and point D_{i+1}, m.

Take (1) into string axle flexural equation $\frac{\mathrm{d}y_i}{\mathrm{d}x^2} = \frac{M(x)}{EI}$, and obtain string bending equation as follows:

$$\frac{\mathrm{d}y_i}{\mathrm{d}x^2}=\frac{1}{EI}\begin{bmatrix}-0.5q_i\cos\alpha_i x^2+(0.5lq_i\cos\alpha_i+M_{1i}/l-M_{2i}/l)x\\-0.5q_i(\sin\alpha_i)xy_i-P_{2xi}y_i+M_{2i}\end{bmatrix}\quad(2)$$

where E is Young's modulus of string, GPa; I is chart moment of inertia of borehole.

When axial force P_{2xi} more than 0, less than 0 or equal to 0, Equation (2) has different analytical solutions. In the process of string running, string neutral point is located at the end of the vertical section or upper of the bending section, string above the neutral point stands tension, $P_{2xi} \leq 0$. However, string of the vertical section is almost no friction, ignoring this friction, and only consider the case of $P_{2xi} > 0$.

When the case is $P_{2xi} > 0$, term of $0.5q_i(\sin\alpha_i)xy_i$, makes analytic solution extremely complex. However, string is restricted by borehole and bending deformation is small, so $y_i << l$. Through the string position of neutral point, compression of string is mainly located in lower-middle bending section and horizontal section, $\cos\alpha_i \neq 0$, so the term of $0.5q_i(\sin\alpha_i)xy_i$ can be ignored. Compared with numerical solution,in the range of string bending, term of $0.5q_i(\sin\alpha_i)xy_i$ can be ignored. We can obtain general solution along with y direction of string axle flexural equation:

$$\begin{aligned}y_i &= k_1\cos(Cx)+k_2\sin(Cx)+q_i\cos\alpha_i EI/P_{2xi}^2+M_{2i}/P_{2xi}\\&+(0.5lq_i\cos\alpha_i+M_{1i}/l-M_{2i}/l)x/P_{2xi}-0.5q_i(\sin\alpha_i)x^2/P_{2xi}\end{aligned}\quad(3)$$

where $C=\sqrt{P_{2xi}/EI}$; k_1, k_2 are the coefficients.

At the point $x = 0$, $\omega_i(0) = 0$, while $x = l$, $\omega(l) = 0$, then the coefficient is:

$$k_1=-q_i(\cos\alpha_i)EI/P_{2xi}^2-M_{2i}/P_{2xi}$$

$$k_2=-\frac{k_1[\cos(Cl)-1]}{\sin(Cl)}$$

Equation (3) on the x derivative, deflection angle of string bending can be obtained as follows:

$$\begin{aligned}\theta_i(x)&=k_1C\cos(Cx)-k_2C\sin(Cx)\\&+(0.5lq_i\cos\alpha_i+M_{1i}/l-M_{2i}/l-q_i\cos\alpha/x)/P_{2xi}\end{aligned}\quad(4)$$

where $\theta_i(x)$ is deflection angle of string at x from point D_{i+1} to string.

2.2 The Mechanical Model of Entire String

Degree of string deflection that is located in two arbitrary contact points can be solved by four forces: Supporting force of point D_i in x, y direction P_{1xi}, P_{1yi}; Supporting force of point D_{i+1} in x, y direction P_{2xi}, P_{2yi} and two shaft torque M_{1i}, M_{2i}, combined with Equation (3). The process of string running can be assume uniform motion, and follow the static equilibrium equation:

$$P_{1xi}+P_{2xi}+q_il\sin\alpha_i-\mu(P_{1yi}+P_{2yi})=0\quad(5)$$

$$P_{1yi}+P_{2yi}=q_il\cos\alpha_i\quad(6)$$

$$M_{1i}+M_{2i}+0.5q_il^2\cos\alpha_i=P_{2yi}l\quad(7)$$

At contact point being situated string and borehole, direction of string bending is the direction of well bore path tangent line.

$$\theta_i(0)+\alpha_i=90°-\gamma_{i+1}\quad(8)$$

where γ_{i+1} is deviation angle of point D_{i+1}.

There is no axial force and bending moment at the foremost end of string where $I = 1$, therefore:

$$P_{1x1}=0\quad(9)$$

$$M_{11}=0\quad(10)$$

The axial force and bending moment of the first section of the string end can be solve by Equations (5) - (10).

The i section and the i-1 section of string have a common point. Two contact forces, forces of the upper end of i-1 section and the lower end of i section, can be action and reaction, therefore:

$$M_{2i-1}=-M_{1i}\quad(11)$$

$$P'_{2xi-1}=-P'_{1xi}\quad(12)$$

where P'_{2xi-1} is axial force of point D_i of i-1 section standing upper string, N; P'_{1xi} is axial force of point D_i of i section standing lower string, N.

Declination angle of point D_i is different to section i and section i-1, and axial force of string can be received by coordinate conversion, the coordinate transformation formula is:

$$\begin{bmatrix}x'\\y'\end{bmatrix}=\begin{bmatrix}\cos\varphi&\sin\varphi\\-\sin\varphi&\cos\varphi\end{bmatrix}\begin{bmatrix}x\\y\end{bmatrix}$$

where φ is the included angle of the original coordinate system shafting to the new one, °; x, y is x, y axis coordinate for the original coordinate system; x', y' is x,y axis coordinate for the new coordinates.

Axial force of section i can be received as follows:

$$P_{1xi}=-\frac{\cos(\alpha_{i-1}+\gamma_i-\pi/2)}{\cos(\alpha_i+\gamma_i-\pi/2)}P_{2xi-1}\quad(13)$$

The axial force and bending moment of section i of the string can be solve by Equations (5) - (8), (11), (13).

When calculating, firstly, calculate axial force and bending moment of the first section, and then sequentially calculate sections upward the second to the neutral point. The upper string above neutral point mainly stays vertical sections and the front of bending sections, almost no friction, and can be solved by the flexible hose model.

2.3 The Calculation Method of Friction and Wellhead Hook Load

The established mechanical model of running friction of multi-stage fracturing string cannot directly calculate the number and position of the contact point, so it can be assumed that the contact point only exists in the position downhole tools and the sidewall as an initial condition. However, with the increase of axial force, string bending deformation among downhole tools increased gradually and contacts the sidewall. We can judge whether sidewall contact with casing in a new point by the location of the center of the string, outside diameter of string, well course and wellbore diameter. The appearance of new contact points will change the strained condition of the string, making the string bend and friction vary, and the calculation method of friction resistance and wellhead hook load is as follows:

(a) Make the initial depth be zero;

(b) At the beginning of each operation, running depth increases a unit depth, assuming that contact points at the down hole tools such as packer, sliding sleeve and so forth;

(c) Take selected and calculated the complete basic data into the relevant basic formula, for $i = 1$;

(d) Calculate string stress and bending of section i. Calculate whether string and sidewall have new contact point or not. If there is a new contact point, calculate the position of the new contact point, and then apply the new position to calculate. If not, making $i = i + 1$, and sequentially calculate the next string stress and bending, until axial force of string $P_{2xi} \le 0$.

(e) The calculation of friction and an axial tensile force of rest of the string utilize the flexible hose model. The axial tensile force of string in wellhead is the wellhead hook load.

(f) Record the calculated wellhead hook load, and return step (b) to calculate running ability of the next depth string. Repeat calculation until the pipe string into the hole.

3. EXAMPLE CALCULATION OF RUNNING FRICTION

In order to verify the accuracy of the model, take X well Hong 90-1 block of Jilin oilfield as an example, compared the calculation by the rigid rod model, the flexible hose modified model and the model of this paper with the measured results in real tripping progress. The parameters of X well and its fracturing completing string is shown in Table 1.

Table 1
Parameters of X Well and Its Fracturing Completing String

Item	Number
Measurement depth	3,257 m
Vertical length	2,048 m
Deflecting bending section length	344.8 m
Horizontal section length	864.53 m
Setting depth of intermediate casing	2,185 m
The depth of completion string	112.51 m
Inside diameter of casing	99.57 mm
Onside diameter of casing	114.3 mm
Casing linear density in drill fluid	172.6 N/m
Drill pipe linear density in drill fluid	116.82 N/m
Young’s modulus of string	208 GPa
Number of fracturing sections	12
Inside diameter of packers	99.57 mm
Onside diameter of packers	146 mm
Number of packers	12
Inside diameter of sliding sleeves	99.57 mm
Onside diameter of sliding sleeves	143 mm
Number of sliding sleeves	12

Casing strings is put into bottom of the well by drill pipe in multi-stage fracturing well, after fracturing, and hang to the end of technical casing through the hanger. Using Visual Basic 6.0 compiles the calculation program of friction and hook load during the process of running string. The calculation of hook load and the measured results are as shown in Figure 3.

When the depth of running string is about 0 m – 1,100 m, casing and down hole tools in the well. The string is short and velocity of running is slow, and the hook load is relatively stable. When the depth of running string is about 1,100 m - 2,100 m, the string is still in the intermediate casing, and drill string with a big length start tripping in from wellhead, and the velocity is fast, almost no uniform velocity in the process, the hook load swing by a large margin and difficult to measure.

When the tripping depth of string is about 2,100 m to bottom, the completion string gradually running into the bending and horizontal section. When string running in the bending section, the hook load calculation accuracy of the rigid rod model, the flexible hose modified model and the model of this paper is 91.45%, 88.10% and 96.57% , respectively. When string running in the horizontal section, the hook load calculation accuracy is 88.03%, 78.88% and 95.45%, respectively. The comprehensive accuracy of three models is 89.11%, 81.79% and 95.80%. Comparing the calculation by three models with the measured results, the calculation model of this paper is consistent in the measured results of hook load, and the established model is more accurate. This model can be used to predict hook load during the process of horizontal well multi-stage fracturing running string, and determine the ability of running string, and also can provide the theoretical basis for structure design and optimization of multi-stage fracturing completion string.

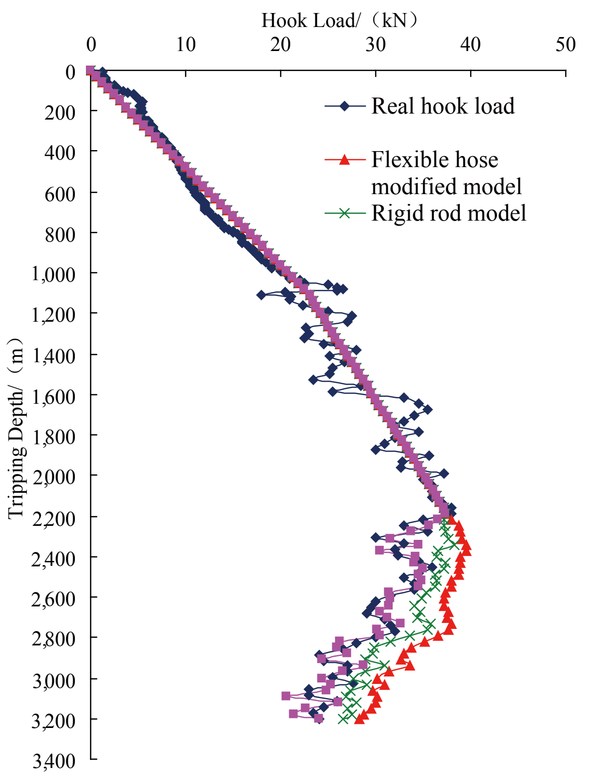

Figure 3
Comparison Between Calculation and Measured Results of the Hook Load

CONCLUSION

(a) Multi-stage fracturing string structure is a complex string which contains packers, sliding sleeves and other downhole tools, outside diameter of downhole tools being large and rigidity being strong, so conventional calculation model cannot meet the accuracy degree.

(b) Comparing the hook load calculation with the actual results of X well Hong 90-1 block of Jilin oilfield, the accuracy rate is as high as 95.80%, the calculated results of the model is accurate and reliable. It can be used to predict the ability of running string, and also can provide theoretical guidance for structure design and optimization.

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