Parameters optimization of release force under top-excited in stuck pipe

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Abstract. Stuck drilling accident is one of the most frequent accidents in the drilling process. The operation time of release drilling is also one of the most time-consuming operations in workover process. In recent years, the technique of release, by drilling string resonance, has been introduced into the drilling field, greatly reducing working hours and improving efficiency. In this paper, the release force's sensitivity analysis is introduced to optimize the design parameters of the device and the working parameters of the release process. First, the pipe vibration behavior under the surface vibration agitator's action is analyzed, and the natural frequencies are obtained analytically. Second, based on Rayleigh damping and specific boundary conditions, the damping effect equation of drilling fluid is derived under drill string vibration. Finally, the influence of structural parameters, environmental parameters, and working parameters on the clamping force is obtained. This paper casts carry through the theoretical interpretation of the release force’s sensitivity analysis by stuck release mechanism and is of significance to optimize the stuck release operations.

1. INTRODUCTION

Accidents of the stuck pipe have been happening ever since drilling began. Furthermore, it is generally divided into differential pipe sticking and mechanical stuck. Differential pipe sticking is an accident in which the drill string is pressed against the borehole wall, when there is a pressure difference between the drilling fluid pressure and the fluid formation pressure. Generally, release operations are adopted, such as changing performance parameters of drilling fluid, washing the stuck drill pipe, reducing the contact area between the borehole wall and drilling tool or drill string, etc., are introduced in [1,2]. The causes of mechanical stuck include key seating, borehole instabilities, hole shrinkage, etc. The stuck release drill's operation is usually the reciprocating movement of the pipe, improving mud circulation times. Moreover, serious accidents may result in the original hole being scrapped, and side drilling may be required. When a serious accident occurs that the drilling tool cannot move freely and the drilling fluid cannot circulate normally, the traditional carding technique cannot be targeted to complete the operation efficiently or even complete the stuck release operation.

Therefore, the kinetic principle of releasing drill string with surface vibration agitator is studied in [3-8]. The vibration device is connected to the top of the pipe and generates an exciting force through the eccentric block's rotation. The exciting force generated by the vibration device is transferred to the drill string. The longitudinal vibration is acted on the stuck point by the pipe. Thus, the cyclic excitation force can be used to solve the stuck problem. It also is testified in [9].
This paper is written as follows: in the first section, the relevant knowledge of the resonance technology and the pipe vibration are introduced. The theoretical equation derivation of the pipe vibration and the damping influence of drilling fluid on pipe is proposed analytically in the second section. The third section introduces the parameter of drilling vibration. The fourth section discusses the sensitivity analysis of the release force under top-excited in a stuck pipe. The final part is the conclusion of the paper.

2. MATERIAL AND METHODS

2.1 Longitudinal vibration formula of a drill string

Each structure of the stuck drilling accident in a vertical well is shown in figure 1 (a). The vibration device is connected with the upper crane hook. The lower part is connected with the drill string. The formation of rock or sand locks the drill string and has a fixed contact boundary. The damping influence of drilling fluid on the pipe is shown by the viscous shear forces on the inside and outside of the pipe.

![Figure 1](image)

Figure 1. Each structure of stuck drilling accident in the vertical well

Based on the infinitesimal element, figure 1(b) shows the forces on a length $\Delta x$ of the pipe. There is derived that the force equilibrium equation:

$$\rho A \frac{\partial^2 u}{\partial t^2} + f_{\text{mud}} = \Delta \frac{\partial \sigma_x}{\partial x}$$  \hspace{1cm} (1)

Where, the vertical displacement of the drill string, density and circular cross section area of the drill string and the Viscous shear force per unit length are $u$, $\rho$, $A$, $f_{\text{mud}}$, respectively. On account of the linear elastic assumption, there is a linear relationship between $\sigma_x$ and strain of the pipe. They are shown as

$$f_{\text{mud}} = 2\pi(\tau_i r_i + \tau_0 r_0)$$ \hspace{1cm} (2)

$$\sigma_x = E \frac{\partial \varepsilon}{\partial x}$$ \hspace{1cm} (3)

Where the Young’s Modulus of the pipe, the inner and outer radii of the drill pipe, the damping effect of drilling fluid are $E$, $\tau_i$, $\tau_0$, $r_i$, and $r_0$ respectively. Based on Newtonian fluid, the damping effect of drilling fluid viscosity is derived as follows:

$$\tau_s = \mu \frac{\partial \nu_{\text{mud}}}{\partial \nu'}$$ \hspace{1cm} (4)

Where, the velocity and the dynamic viscosity of the mud $v_{\text{mud}}$ is and $\mu$. Based on that there is a linear relationship between the viscous shear stress and the relative velocity of the pipe, the shear force can be written as

$$f_{\text{mud}} = C_d \frac{\partial \mu}{\partial t}$$ \hspace{1cm} (5)

Where the viscosity of the drill mud, the geometry of the drill string and the bore determine this constant $C_d$. The analytical expressions of derived parameters $C_d$ are based on Newtonian fluid and laminar flow. Thus, the vibration equation of drill string can be converted into the Partial differential formula are shown below:
\[ \rho \frac{\partial^2 \mu}{\partial t^2} + C_\mu \frac{\partial \mu}{\partial t} = E_A \frac{\partial^2 \mu}{\partial x^2} \]  
(6)

Based on the established model, the boundary condition \( x = 0 \) (stuck point) is 
\[ \mu(0, t) = 0 \]  
(7)

The boundary condition \( x = L \) (the connection between the pipe and the stuck release device) is 
\[ m_s \frac{\partial^2 \mu}{\partial t^2} \bigg|_{x=L} = f(t) - k_s \mu(L, t) - E_A \frac{\partial \mu}{\partial x} \bigg|_{x=L} \]  
(8)

Where the mass of the vibration device is represented by \( m_s \), the suspension spring's stiffness is represented \( k_s \).

In the vibration model of the drill string, it is assumed that the pipe is fixed at the stuck position. This makes sense because the drill string is longer in length. However, each stuck section's drill string vibration model needs to be rewritten in the pipe string with multiple stuck sections. Only the longitudinal vibration of vertical borehole bore string is considered in this study. For simplicity, Other deformation conditions of the pipe and extrusion resulting from the contact of the pipe with the borehole are ignored.

2.2 Natural frequency of the vibration system

The system's natural frequency can be obtained by deducing the vibration balance equation under the condition of undamped. Based on the fact that the displacement is separable, the natural frequency can be obtained. That is 
\[ \mu(x, t) = Y(x)G(t) \]  
(9)

Thus, 
\[ \tan(xd_s) = \frac{E_A}{m_sL(o^2 - \omega^2)} \]  
(10)

\[ \omega^2 = \frac{k_s}{m_s} \]  
(11)

2.3 Fluid induced damping effect

In the actual circulation process, the drilling fluid passes into and out of the drill string through the circular space between the drill string and the borehole wall. Since the composition mechanism of damping force is more complex, such as contact with a good wall, a viscosity of drilling fluid and so on, it is very difficult to construct damping matrix directly; the damping matrix commonly used now is Rayleigh damping, also called proportional damping [10], which is obtained by the linear combination of mass matrix \( M \) and stiffness matrix \( K \), that is, expressed as:

\[ C = \beta M + \beta K \]  
(12)

Where \( \phi, \beta \) is the Rayleigh damping coefficient.

2.4 Numerical modeling

For the vibration balance equation of the drill string established above, the finite element method is used to solve it, as shown in figure 2. Assuming that the bottom of the pipe is fixed at the fixed point, the vibration result of the drill string is obtained by solving equation 6

Figure 2. Schematic diagram of the finite element method

The vibration equation under the damping condition of drilling fluid is as follows.

\[ \int_0^L w(x) \rho \bar{u} \mu dx + (4\mu + C_\mu) \bar{u} \mu dx = E_A \int_0^L \frac{\partial^2 \mu}{\partial x^2} dx \int_{-L}^L w(x) (E \bar{u} \mu) dx \]  
(13)

Where the solution space and the weighting space are 
\[ F = \{ \bar{u} | \bar{u}(0, t) = 0, \} \]  
(14)
Based on the finite element model, the relevant mass matrix, damping matrix, and stiffness matrix are as follows.

\[
M = \frac{\rho ML}{6} \begin{bmatrix}
    4 & 1 & 0 & 0 & 0 & 0 \\
    1 & 4 & 1 & \cdots & 0 & 0 \\
    \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
    0 & 0 & 0 & 0 & 1 & 2 + \frac{\omega_n}{\rho ML} \\
\end{bmatrix}
\]

\[
C = \rho M + \beta K
\]

\[
K = \frac{EA}{\delta}
\begin{bmatrix}
    2 & -1 & 0 & 0 & 0 & 0 \\
    -1 & 2 & -1 & \cdots & 0 & 0 \\
    \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
    0 & 0 & 0 & 0 & -1 & \frac{k_{EA}}{EA} \\
\end{bmatrix}
\]

The excitation force is generated of the vibration device, so the vector of the force is written as

\[
F = \begin{bmatrix} 0 & 0 & \cdots & f(t) \end{bmatrix}^T
\]

The eccentric force is written as

\[
f(t) = m_{ecc} r_{ecc} \omega^2 \sin(\omega t)
\]

3. RESULTS AND DISCUSSION

The system parameters used in this study are pipe geometry, material characteristics, structural parameters and environmental parameters. They are shown in table 1.

| Environmental parameters | Structural parameters |
|--------------------------|-----------------------|
| \(E/\text{GPa}\) | \(r_1/\text{mm}\) | \(r_2/\text{mm}\) | \(M/\text{cp}\) | \(m_2/\text{kg}\) | \(k_s/\text{N}\cdot\text{m}^{-1}\) | \(m_e/\text{kg}\) | \(r_e/\text{mm}\) |
| 210 | 48.59 | 57.15 | 15 | 800 | 5 × 10^5 | 800 | 500 |

For this research institute on the assumption that the pipe is a constant circular cross-section pipe regardless of dimensional change caused by the drill string joint. Vibratory agitator driven by an electric or hydraulic motor, vibration force is produced by eccentric block, the relevant parameters are shown in table 1.

3.1 Vibration characteristics of pipe

The energy generated by the vibrating device is transmitted to the sticking location by the pipe. In the case of undamped and perfect-linear elasticity, the resonance amplitude of drill string tends to infinity. Under the action of the drilling fluid damping established in this study, the resonance amplitude of the drill string will tend to be a steady-state to achieve the steady-state resonance effect.

The accumulation of releasing force under resonant excitation of order four is shown in figure 3. It can be observed that the displacement of the drill string at different depth increases under resonance excitation. However, the presence of drilling fluid acts as a damper, limiting the vibration amplitude of pipe to a steady-state, as shown in Figure 4.
3.2 Parameters optimization of release force

For the on-well vibrator, the exciting force generated by the vibrator makes the vibrator-drilling system achieve resonance, and the clamping force at the clamping point is used. During the whole process, the uncharitable force is affected by the dynamic viscosity of the drilling fluid, the top displacement excitation force, the good depth, the friction, and the vibrator's parameters. To study the influence law of each factor on the force of uncorking, the influence law of each factor on the force of uncorking is studied based on the vibration mechanics model of the vibrator-drilling string system. At the same time, in order to reflect the influence of different factors on the steady-state clamping force at different vibration frequencies, such as the third, eighth, thirteenth and eighteenth nature frequencies, resonance is taken frequency analysis respectively.

3.2.1 Drilling fluid viscosity

Dynamic viscosity of the drilling fluid is an important parameter affecting the amplitude of the release force. The steady-state release force is calculated by setting the Rayleigh coefficient; the results are shown in figure 5.

Figure 5. Evolution of steady-state force with dynamic Rayleigh coefficient

Figure 5 shows the variation of steady-state release force with different Rayleigh coefficient under different resonance frequency signals. The diagram shows a downward trend under the influence of the Rayleigh coefficient, the steady-state release force of the resonance frequency signals of each order shows a downward trend. With the different resonance frequency changes, the steady-state force at the
fixed location is affected by the Rayleigh coefficient. Therefore, the optimal steady-state release force should be obtained by adjusting the dynamic viscosity of drilling fluid.

### 3.2.2 Excitation Force

![Figure 6. Evolution of steady-state force with motivation force](image)  

Figure 6 shows the change course of steady-state force with motivation force at different resonance frequency signals. It can be seen from the figure that the steady-state force of each order is linearly related to the excitation force, which increases with the increase of the excitation force, the steady-state solution clamping force of the 13th order resonance frequency increases most in each order resonance frequency.

### 3.2.3 Well depth

![Figure 7. Evolution of steady-state release force with drill string length](image)  

Figure 7 shows the evolution of steady-state release force with different good depths at the stuck point under different resonance frequency signals. It can be seen from the figure that with the increase of good depth, the steady-state release forces of each order show an attenuation trend. In each order resonance frequency, the steady-state solution release force generated by the 13th order resonance frequency is always the maximum. Therefore, the optimal resonance frequency can be selected for deep wells in practical card-relief operations. The purpose of fast card-relief is achieved by adjusting the exciting force of the vibrator.

### 3.2.4 Structure Parameters of Vibrator

The vibrator's structural parameters of the vibrator are the key to obtaining the optimal solution of the release force, so it is necessary to consider the damping of the vibrator and the stiffness. The influence of the vibrator's structural parameters of the vibrator on the clamping force is analyzed, and the concrete results are shown in figures 8 and 9.
Figure 8 shows the change course of steady-state release force with different damping conditions of the vibration decamping device. It can be seen from the figure that the steady-state release force at each order resonance frequency shows an attenuation trend with the increase of damping of the vibrator. In different resonance frequencies, the steady-state release force's attenuation degree slows down with the increase of the order of the resonance frequency. Figure 8 shows the steady-state release force's variation under different stiffness conditions of the vibration decamping device. It can be seen from the diagram that the resonance frequencies of each order show different trends with the increase of stiffness. At the low order resonance frequencies (order three and order 8), the steady-state force follows the stiffness with the increase of degree. The steady-state force decreases with the increase of stiffness at higher resonance frequencies (13th and 18th). Therefore, in the structural design of the vibrator, in order to obtain a large release force, we should reasonably consider the design of damping stiffness in the structural parameters of the vibrator.

4. CONCLUSIONS
In this paper, the sensitivity analysis of the release force to different parameters under the action of the top-excited cyclic load is studied. The details are as follows:

Firstly, the dynamic vibration balance equation of the pipe under the action of the eccentric-block vibration device is established. Based on Rayleigh damping and specific boundary conditions, the damping effect equation of drilling fluid is derived under drill string vibration.

Second, the damping produced by the dynamic viscosity of drilling fluid has an influence on the amplitude of the steady-state force, especially at the high-order resonance frequency.

Finally, at the same resonance frequency, the dynamic viscosity of drilling fluid and well depth in the vibrator structure have a great influence on the steady-state uncorking force. And at different frequencies, the release force presents an optimal interval.

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