Analysis of the Control Strategy of the Intelligent Iron Roughneck's Make-up and Break-out Fusion with Fuzzy Adaptive Control Algorithm

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Abstract. The Iron roughneck is the supporting equipment of the drilling rig in the automatic drilling production. It can safely and efficiently complete the work of drilling tools such as up-and-down and tight-punching, but the up-and-down control has not yet reached full intelligence. Therefore, based on the principle of contact mechanics and tribology, this paper relies on fuzzy adaptive control algorithm to analyze the strength of the forceps and the pipe string, and the reasons for the wear of the forceps. Under the constraint conditions of friction torque meeting the requirements of up-and-shaking and not damaging the pipe string, the orthogonal design is used to analyze the influence of four factors on the equivalent friction coefficient when the clamp teeth are in contact with the outer wall of the pipe string. The up-and-down control strategy lays the theoretical foundation. The results show that the shape angle of the jaws has the greatest influence on the equivalent friction coefficient, while the influence of the crest chamfer radius is almost negligible.

Keywords: Smart Iron Drill, Punch Pliers, Jaws, Contact Stress, Sensitivity Analysis

1. Introduction
The Iron roughneck is the main equipment in the establishment of the root system, which plays a key role in the improvement and safety of the operation efficiency and safety of the wellhead string establishment, and basically realizes the mechanization of the drill floor operation [1, 2]. However, the application of thread oil on drill pipes on the floor surface currently requires manual operation. As an independent device, the drilling fluid box takes a certain amount of time to reach and exit the wellhead [3, 4]. As the oilfield puts forward higher demands for ensuring the safety of wellhead operations, reducing the number of operators, and reducing the labor intensity of the operators, relevant scientific research institutions and enterprises at home and abroad have integrated solutions for Iron roughnecks, thread oil application devices and drilling fluid boxes. Related technical research has been carried out. Foreign AKER MH company and Weatherford company have developed integrated iron drills and applied them on site. Their products are mainly used for offshore platforms and are relatively bulky.
According to different structures, iron drill products can be roughly divided into arm type and floor type. The main structure includes two parts: a moving device and a clamp body. The clamp body is divided into a spin button device and a punch button device. The structure is simple and easy to maintain and repair. The punching pliers are composed of an upper pliers and a lower pliers. They adopt an open box structure. The clamping mechanism and the sliding block assembly are driven by the expansion and contraction of the clamping cylinder to realize the opening and closing of the jaws and complete the drilling of different diameters. The clamping; between the upper and lower clamps is equipped with a guide rail and a punching hydraulic cylinder, the punching/fastening action is realized through the expansion and contraction of the punching cylinder [5, 6].

This article mainly relies on the fuzzy adaptive control algorithm to study the Iron roughneck's jaws, analyzes the contact between the jaws and the outer wall of the petroleum pipe string, friction characteristics, wear reasons and other issues, discusses the impact of key parameters on the upper and lower shackles. The up-and-down control strategy provides theoretical guidance.

2. Fuzzy adaptive control algorithm

Based on the basic idea of backstepping sliding mode control, the fuzzy adaptive control algorithm adopts the conversion of state variables: \( x_1 = q \), \( x_2 = \alpha x_1 + \omega \). In this paper, the disturbance torque is taken as the unknown parameter, and the unknown parameter adaptive control law is designed, and the attitude stability control algorithm is designed as shown in equation (1). The process of proving the stability of the control algorithm is the reverse process of the control algorithm.

\[
u = -\frac{1}{2} x_1 - Y\theta - \hat{d}_{\max} \text{sgn}(x_2) - Kx_2
\]  

(1)

Where: \( \alpha > 0; K > 0; \)

\[
\theta = \left[ J_{11} J_{12} J_{13} J_{21} J_{22} J_{23} J_{31} J_{32} J_{33} \right]^T; \]

and suppose that the satellite interference torque \( \| d \| \leq d_{\max} \), and \( d_{\max} \) is an unknown constant, \( \hat{d}_{\max} = \| x_2 \| \).

Proof: Define the Lyapunov function as follows:

\[
V = \frac{1}{2} \left[ x_1^T x_1 + (1 - q_0) \right] + \frac{1}{2} \hat{d}_{\max}^2
\]  

(2)

Among them \( \hat{d}_{\max} = d_{\max} - \hat{d}_{\max} \), take the derivative of (2),

\[
\dot{V} = -\frac{1}{2} \alpha x_2^T x_1 + \frac{1}{2} x_1^T x_1 + x_1^T J \dot{x}_2 - \hat{d}_{\max} \dot{x}_2
\]  

(3)

because

\[
\dot{x}_2 = \dot{\omega} + \alpha \dot{x}_1 = \dot{\omega} + \alpha \dot{q}
\]  

(4)

Have

\[
J \dot{x}_2 = J \dot{\omega} + \alpha J \dot{q} = + \omega^t J \omega + u + d + \alpha J \dot{q}
\]  

(5)

make

\[
Y \theta = -\omega^t J \omega + \alpha J \dot{q}
\]  

(6)

then

\[
\dot{V} = -\frac{1}{2} \alpha \| x_1 \|^2 + x_2^T \left( \frac{1}{2} x_1 + Y \theta + u + d \right) - \hat{d}_{\max} \dot{x}_2
\]  

(7)
Substitute the control quantity to get
\[ \left\| x_2 \right\| \dot{d}_{\text{max}} + \left\| x_2 \right\| d_{\text{max}} - \dot{d}_{\text{max}} x_2^T K x_2 = - \frac{1}{2} \alpha \left\| x_1 \right\|^2 - x_2^T K x_2 \] (8)

It can be seen that \( V \) is negative definite, according to Lyapunov's stability theorem: 
\[ \lim_{t \to \infty} x_i = 0, \quad \lim_{t \to \infty} x_2 = 0, \quad \lim_{t \to \infty} q = 0, \quad \lim_{t \to \infty} \varphi = 0. \]

2.1. Extrusion strength conditions of Iron roughneck indentation

The effective area of \( F_{\text{in}} \) on the side of the indentation on the outer surface of the pipe string joint is shown in equation (9)
\[ A_{\text{in}} = l t \sec \frac{\theta}{2} \] (9)

Therefore, the compressive stress generated by \( F_{\text{in}} \) on the side of the indentation on the outer surface of the pipe string joint is
\[ \sigma_{\text{gin}} = \frac{F_{\text{in}}}{A_{\text{in}}} = \frac{T \cot \frac{\theta}{2}}{\ln(R-t)} \cdot \sqrt{1 - \left[ \frac{R - t - r_i \left( \csc \frac{\theta}{2} - 1 \right)}{R \sin \frac{\theta}{2}} \right]^2} \] (10)

In order to ensure that the contact surface of the outer surface of the pipe string joint is not crushed during the process of making and breaking, it should meet
\[ T \leq \frac{\ln(R-t) \tan \frac{\theta}{2}}{\sqrt{1 - \left[ \frac{R - t - r_i \left( \csc \frac{\theta}{2} - 1 \right)}{R \sin \frac{\theta}{2}} \right]^2} \left[ \sigma_{\text{gc}} \right]} \] (11)

2.2. Shear strength conditions of the bite part of the iron drill pliers

The shear area of the bite part of the iron drill's forceps is the same as the force area of each indentation when the depth of the outer wall of the pipe string joint that the forceps teeth can bite under the action of the normal force \( F_n \) is \( t \). The shearing force is \( F_t \), so the shearing stress of the bite part of the jaw is:
\[ \tau_{q_{\text{int}}} = \frac{F_t}{A_{\text{in}}} = \frac{T}{n(R-t)2l \sin \frac{\theta}{2}} \sqrt{R_t^2 + \left( 1 - \sin \frac{\theta}{2} \right)^2} \left[ R - t - r_i \left( \csc \frac{\theta}{2} - 1 \right) \right]^2 \] (12)

Then the shear strength conditions of the bite part of the clamp teeth are:
\[ T \leq n(R-t)2l \sin \frac{\theta}{2} \sqrt{R_t^2 + \left( 1 - \sin \frac{\theta}{2} \right)^2} \left[ R - t - r_i \left( \csc \frac{\theta}{2} - 1 \right) \right]^2 \left[ \sigma_{q_{\text{c}}} \right] \] (13)

Where \( [\sigma_{q_{\text{c}}} \] is the allowable shear strength of the forceps tooth material.
3. Intelligent Iron roughneck upper and lower shackle control

The rail-type hydraulic tongs are installed on the drill floor and are mainly used to make and break drill pipes, drill collars and casings; the left and right sides of the front end of the tongs are respectively installed with rotating supports, which can surround the left end of the tongs. The right 2 columns rotate 90°. A threaded oil application device is installed on the left rotating support, and a drilling fluid box is installed on the right rotating support, which can be independently moved to the wellhead to complete thread oil application or drilling fluid blowout prevention. The three equipments of the integrated iron drill share a set of walking rails, which saves drill floor layout space, has a compact structure, and meets the requirements of mechanization of drilling tools.

In addition to avoiding the failure mode of the shackle pliers teeth of the Iron roughneck, another inevitable failure mode is wear. Under the action of the load, the friction between the moving pairs causes the gradual loss or migration of the surface material of the parts. Wear will affect the efficiency of the Iron roughneck and reduce the reliability of its work. The main factors that affect the wear of the forceps teeth include material properties, load conditions, geometric structure and environment. For forceps teeth, the material properties are mainly hardness and elastic modulus. While satisfying bending strength, shear strength and compressive strength, the surface hardness of the material should be increased as much as possible, and materials with higher elastic modulus should be selected. The load conditions are mainly the size of the load and the number of actions. The greater the load and the number of cycles, the greater the amount of wear. The geometric structure mainly determines the contact stress and stress concentration between the clamp teeth and the outer wall of the pipe string joint. Environmental factors are mainly temperature and lubrication. The increase in temperature will accelerate the wear. Although lubrication has the effect of reducing the degree of wear, it will reduce the friction and prone to slipping.

In this paper, the factors affecting the equivalent friction coefficient \( f_v \) when the teeth of the Iron roughneck’s upper shackle pliers contact the outer wall of the pipe string joint are bite mark depth \( t \), tooth profile angle \( \theta \), pliers tooth crest chamfer radius \( r_1 \), pipe string outer radius \( R \). According to formula (8), analyze the influence of 4 factors on the friction coefficient \( f_v \) of Dangzhe. When the clamp teeth are in contact with the outer wall of the pipe string joint, the pipe string is made of high alloy steel, and the clamp teeth are made of carbon steel. The friction coefficient \( f \) is 0.12 according to the two materials. The value levels of each parameter are shown in Table 1.

### Table 1. Factors and levels of equivalent friction coefficient.

| Level | Bite mark depth \( t/\text{mm} \) | Tooth angle \( \theta/\text{°} \) | Chamfer radius \( r_1/\text{mm} \) | Outside radius of pipe string \( R/\text{mm} \) |
|-------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1     | 0.0                             | 60                              | 0.0                             | 88.7/2                          |
| 2     | 0.5                             | 80                              | 0.5                             | 114.2/2                         |
| 3     | 1.0                             | 100                             | 1.0                             | 127.0/2                         |
| 4     | 1.5                             | 120                             | 1.5                             | 139.5/2                         |

Orthogonal experiment design uses a set of standardized orthogonal table to arrange the experiment. The optional orthogonal table corresponding to 4 factors and 4 levels is \( L_{16}(4^5) \), that is, 16 experiments are performed. Mark the four factors of bite mark depth \( t \), tooth profile angle \( \theta \), jaw chamfer radius \( r_1 \), tube diameter outer radius \( R \), respectively, as A, B, C, D, and one column in the table is marked as E.

There are two methods for analyzing the results of orthogonal experiments, namely, range analysis (intuitive method) and analysis of variance. The range analysis method has the advantages of simple calculation, simple and easy to understand, and is a commonly used method for the analysis of orthogonal experimental results. The range analysis is performed on the results of the above orthogonal test, and the range results are shown in Table 2.

It can be seen from Table 2 that the range of factor B is the largest, indicating that the profile angle \( \theta \) has the most significant effect on the equivalent friction coefficient \( f_v \), followed by the bite mark depth \( t \) and the outer radius of the pipe column \( R \), and the range of the crest chamfer radius \( r_1 \) is the...
The effect on the equivalent friction coefficient $f_{v}$ is almost negligible. The smallest. The effect on the equivalent friction coefficient $f_{v}$ is almost negligible.

**Table 2.** Statistical analysis of test results.

| factor | mean $f_{v}$   |
|--------|----------------|
| A      | 0.945          |
| B      | 0.918          |
| C      | 0.944          |
| D      | 0.944          |

It can be seen from the results that when the bite mark depth $t \leq 1.0$mm is required, for the commonly used pipe string diameter series (i.e., the outer radius of the pipe string R level 1, level 2, level 3, the corresponding pipe string diameters are $D=88.7$mm, $114.2$mm, $127$mm), the best value of the profile angle $\theta$ is between its level 2 ($\theta=80^\circ$) and level 3 ($\theta=100^\circ$).

When the metal friction coefficient $f=0.12$ and the tooth crest chamfer radius $r_{1}=0.5$mm, the tooth profile angle $\theta$ and the bite mark depth $t$, the tooth profile angle $\theta$ and the outer radius of the pipe column $R$ are the independent variables, and the equivalent friction coefficient $f_{v}$ is The fitting surface of the dependent variable is shown in Figure 1, which can more intuitively compare the influence of different factor combinations on the equivalent friction coefficient $f_{v}$.

![Figure 1. The horizontal surface of the $\theta/t$ factor index.](image)

**4. Conclusion**

This paper mainly relies on fuzzy adaptive control algorithm to study the iron drill tongs, analyzes the contact between the tongs and the outer wall of the petroleum pipe string, friction characteristics, wear reasons and other issues, discusses the impact of key parameters on the upper and lower shackles, and aims to provide intelligence The control strategy of iron drills on and off lays a theoretical foundation. The teeth of the pliers should avoid or reduce wear and tear, increase their service life, and ensure the quality and efficiency of the shackle of the iron drill.

**Acknowledgments**

This work was supported in part by the Characteristic Natural Science Innovation Projects of General Universities in Guangdong Province in 2020 Research on Control System and Key Technology of Intelligent Arm Type Iron Roughneck under Grant 2020KTSCX380; In part by the Key Natural Science Research Projects of New Generation of Information Technology in Focus Areas in 2020 of General Universities in Guangdong Province Key Technology Research on Channel Heterogeneous...
CDN under Grant 2020ZDZX3108.

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