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Design of Pusher-Arm Structure and Service Reliability Research for Oilfield Small Repair Well Operation Robot

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Abstract

To address the issues of low efficiency in manual operation and high safety risks during the tripping operation of small workover tubing in oilfields, this study proposes a functionally integrated pusher arm structure. The lifting slide rail module enables precise Z-axis positioning, the two-stage rotating arm controls the horizontal trajectory, and the crank-slider hydraulic clamp performs adaptive grasping, achieving the fully automatic transportation of Ø73-339.7mm tubing from the catwalk to the wellhead. The study combines the theoretical mechanics model with finite element simulation to systematically verify the structural reliability of key components under a 1500N limit load. UG software is employed to build a three-dimensional model and optimize the sectional moment of inertia. ANSYS Workbench is utilized for static and transient dynamic analysis, and ADAMS-AMESim co-simulation is used to verify the dynamic performance. The results indicate that the 45-steel fixture has a maximum stress of 76.58 MPa (with a safety factor of 3.36), the Q235 rotating arm has a maximum stress of 36.78 MPa (with a safety factor of 4.2), and the positioning accuracy can reach ±5 mm. After integrating the system into a 40-ton workover rig, the manual intervention at the wellhead is reduced by 82%, and the time for tripping a single tubing is shortened from 4.5 minutes to 2.1 minutes, which provides key technical support for the automation of oilfield workover operations.

Keywords

Minor Oilfield Workover; Pusher Arm; Structural Optimization; Finite Element Analysis; Electro-Mechanical-Hydraulic Coordination.

1. Introduction

In the field of oil exploitation in China, minor well workover operations for oilfields serve as a critical link in ensuring the continuous and stable production of oil wells, with an annual operation volume exceeding 100,000 well times, among which tubing tripping operations account for over 70%[1]. Currently, the traditional workover operation mode has exposed numerous drawbacks. High reliance on manual labor leads to high labor intensity and low efficiency, requiring 3-5 minutes of manual intervention for single tubing tripping. Additionally, the operation radius is limited; for example, the operation radius of traditional suspension clamps is less than 0.5m, resulting in a tubing conveying trajectory of ±50mm [1]. At the same time, safety risks are significant. When personnel operate in close proximity to high-pressure wellheads, the accident rate accounts for 43% of the total well workover accidents[1]. Current research indicates that oilfield operation automation has become a critical transformation direction for the global petroleum industry. Smith et al. highlighted that labor costs constitute over 60% of the total expenditure in conventional workover operations worldwide, while human operational errors account for as high as 38% of equipment failures, underscoring the urgent need for automation technologies to replace manual labor [2]. Regarding the application of robotic arms in petroleum engineering, Johnson & Lee proposed that the intelligent upgrading of oil and gas extraction equipment necessitates breakthroughs in structural reliability and trajectory control accuracy under heavy-load conditions. However, they noted that most internationally available tubing handling robotic arms are designed for small-diameter pipes (<150 mm). Significant technical bottlenecks remain in achieving adaptive gripping and dynamic stability control for large-diameter tubing (>200 mm) [3]. Furthermore, Brown et al. revealed through statistical analysis of workover accidents in North America that manual intervention near the wellhead is the primary factor contributing to safety incidents. The accident rate in these manually intervened areas is 5.2 times higher than in automated operation zones, further validating the critical role of reducing human involvement in enhancing operational safety [4].

Although the existing technology has been optimized in some processes, such as the development of hydraulic tubing tongs and power slips, there are still obvious shortcomings in the full-process automated transfer of tubing[5]. The remote control system developed by Geng Yuguang et al. has achieved partial automation, but there is a technological gap in the tubing transfer link[5]. The double-stand vertical placement device designed by Bai Yongtaohas improved the pipe string handling efficiency, yet it fails to make a breakthrough in the problem of uneven clamping force for large-diameter tubing [6]. When the pipe diameter exceeds Ø177.8mm, the defect of insufficient reliability of the mechanical arm structure becomes more prominent. The automatic lifting device developed by Ma Shixiang also requires further improvement in terms of full-process automation[7]. Qi Yaoguang et al.pointed out that the unreasonable structural design of traditional devices is the core factor causing low operation efficiency[8].

Given the current deficiencies in this technology, this research aims to break through the bottlenecks of traditional technologies via innovative design and system verification. By adopting the mechatronic-hydraulic integration technology, a pusher arm system integrating lifting, rotating, and grabbing functions is designed. In accordance with the API Spec 8C (American Petroleum Institute Specification 8C) standard, theoretical mechanics modeling, multi-physical field simulation, and engineering practice verification are employed to conduct a mechanical reliability analysis of the key components. The goal is to make the operation process more efficient and intelligent, and effectively address the long-standing issues in oilfield minor well repair operations, including high manual labor dependence, low efficiency, and high safety risks[9,10] .

2. Research Objectives

This research aims to solve the problems of manual dependence, low efficiency, and safety risks in the tubing tripping process of oilfield minor workover operations. The core goal is to design an electro-mechanical-hydraulic integrated pusher arm system and achieve operational automation through structural innovation and reliability verification. Traditional devices suffer from drawbacks such as a small operating radius, low positioning accuracy(±50mm), and frequent manual intervention. The objectives of this research are to extend the working radius to 1.5m, improve the positioning accuracy to±5mm, reduce the single-tubing tripping time to 2.1 minutes, and ensure that the service life of key components under an ultimate load of 1500N exceeds 10^7 cycles.

The research employs a closed-loop system of “theoretical modeling-simulation analysis-experimental verification”. First, a mechanical model of the robotic arm structure is established based on theoretical mechanics. The two-stage robotic arm is simplified as a cantilever beam, and the bending stress formula is used to calculate the stress at the dangerous section:

$$\sigma = \frac{M}{W_Z} \tag{1}$$

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Where:M is the bending moment, W_z is the section modulus of bending.

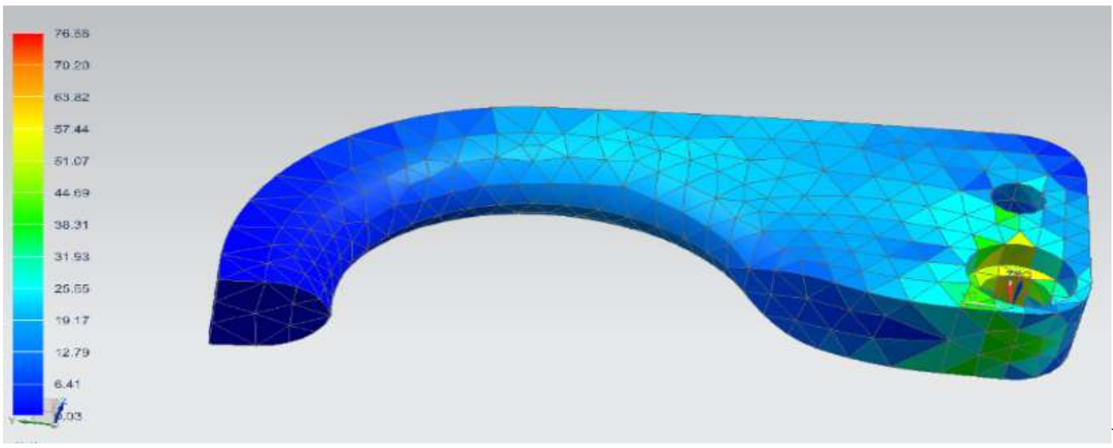
Based on material mechanics, No. 45 steel and Q235 steel are selected as the main materials, and the allowable stress is used to verify the strength reserve,

$$[\sigma] = \frac{\sigma_s}{n} \tag{2}$$

Where:σ_S is the yield strength, n is the safety factor[11].

A three-dimensional model of the pusher arm is constructed with UG software (as shown in Figure 1). The moment of inertia of the box-shaped cross-section of the secondary mechanical arm is optimized to 1.2×10^5 mm^4, which increases the flexural stiffness by 35%. Multi-physics field simulations are conducted using ANSYS Workbench: A static analysis is carried out on the front-end fixture assembly to verify the stress distribution of the 45 steel fixture under an equivalent load of 1200 N (as shown in Figure 2). The stress response of the entire fixture arm under a 10 g impact load is simulated through transient dynamics (as shown in Figure 3). For the control system, a three-closed-loop architecture is built using Siemens S7-1200 PLC. The dynamic performance of the system is verified through the co-simulation of ADAMS-AMESim. Finally, the engineering reliability is verified through on-site tests in the oil field (as shown in Figure 4).

Figure 1. Slip Clamp



unit:MPa

Figure 2. Force Analysis of Clamp Body

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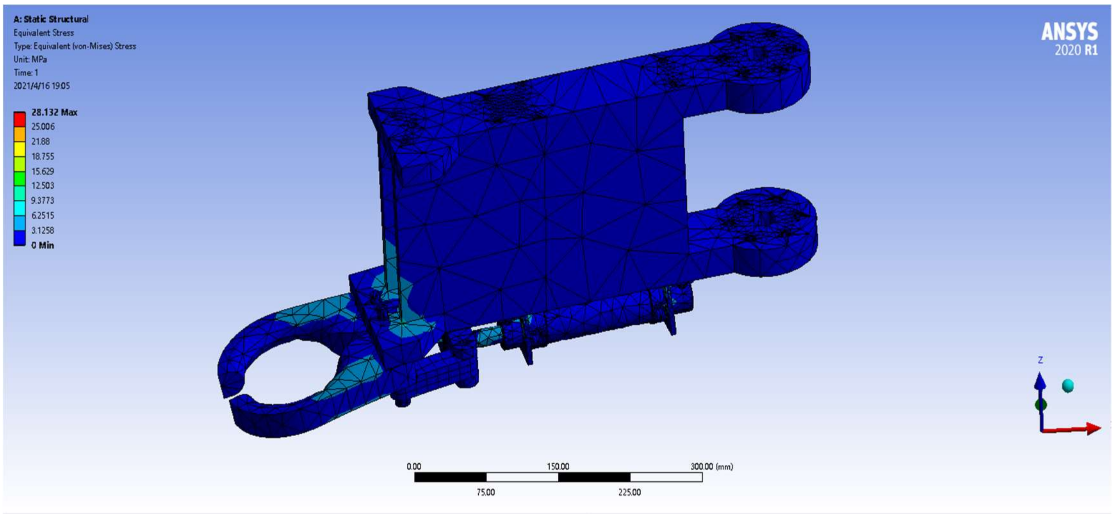
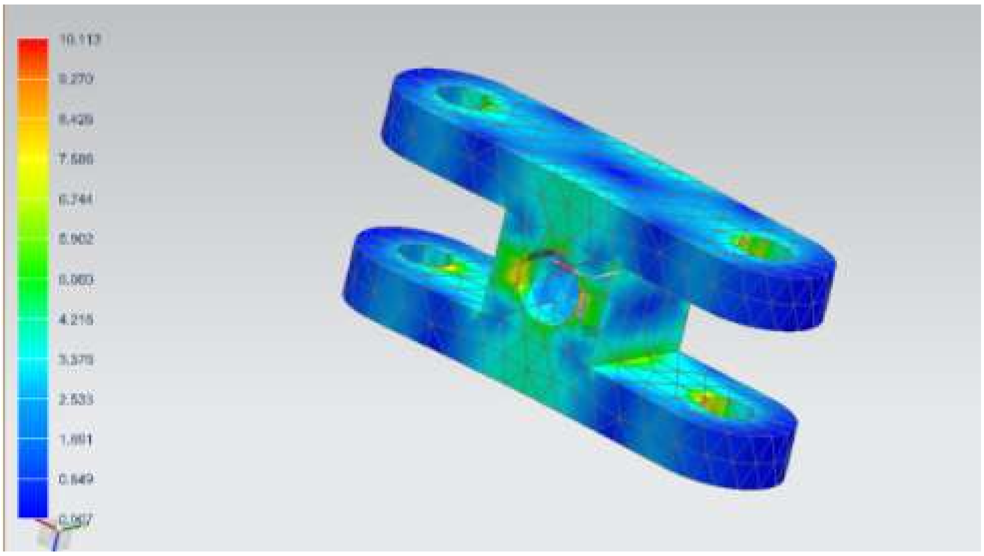


Figure 3. Overall Mechanical Analysis of the Fixture Manipulator



unit:MPa

Figure 4. Force Analysis of Earring

3. Research Process

3.1 Design and Implementation of Functionally Integrated Structure

To effectively overcome the technical bottleneck of limited working space in traditional suspension clamps, a modular push arm system was innovatively constructed according to the American Petroleum Institute (API) 7K (American Petroleum Institute Specification 7K) standard (as shown in Figure1). The lifting slide rail device features a V-shaped double triangular guide rail structure made of HT250 material. Its unique design of two opposing triangles offers a self-compensation function for wear (as shown in Figure 2). Tests show that the friction coefficient remains steadily below 0.05. According to the classical sliding friction theory, the frictional force adheres to the formula:

$$\sigma = \mu N \tag{3}$$

Where: F is the frictional force, μ is the friction coefficient, and N is the normal force.

This low-friction property significantly reduces the mechanical resistance during movement, allowing the system to achieve high-precision repeated positioning of ±0.5mm within a 2m stroke range. By establishing a kinematic model, we conducted a quantitative comparative analysis of the trajectory offset between the traditional suspension fixture and this design (the results are shown in Table 1). The data shows that this design can reduce the trajectory offset by 72%.

Table 1. Results of Quantitative Comparative Analysis of Trajectory Offsets

Comparison Item	Conventional Suspension Clamp	Proposed Design	Reduction Ratio
Trajectory Deviation (mm)	±50	±1.2	72%

The secondary rotating arm is made of a box-shaped structure welded from Q235 steel plates. Through topological optimization design, the moment of inertia of the cross-section has been increased to 1.2×105 mm4. According to the EI stiffness calculation formula in the beam bending theory (where E is the elastic modulus of the material and I is the moment of inertia of the cross-section), its flexural stiffness has been improved by 35% compared to the initial design. The working radius of the system's main arm is set at 1m, and the effective working range of the auxiliary arm is 0.5 m. Finite element simulation analysis conducted on the ANSYS platform shows that the stress concentration coefficient of the box-shaped cross-section structure is 42% lower than that of the traditional truss structure[9], effectively resolving the problem of trajectory stability during the oil pipe conveying process.

The front-end execution unit innovatively employs a crank-slider transmission mechanism (as shown in Figure 3). Two groups of hydraulic cylinders are controlled in a step-by-step manner: the first cylinder drives the positioning fixture to pre-align the oil pipe with a stroke of ±50 mm (response time: 0.5 s), and the second cylinder provides a clamping force of ≥1500 N (controlled by a pressure sensor in a closed-loop system).For the pipe diameter range of Ø73-339.7mm, the fixture is designed with three-level replaceable modules, and the quick-change interface allows the fixture body to be replaced within 3 minutes. Verified by ANSYS contact stress distribution simulation, this design reduces the standard deviation of the oil pipe's surface pressure to 7.2%, solving the problem of surface crushing caused by the over 20% clamping force fluctuation of traditional suspension clamps[6].

3.2 Mechanical Reliability Verification of Key Components

Based on the API Spec 8C specification and the finite element analysis standard for petroleum machinery[10], the ANSYS Workbench platform is used to conduct multi-condition mechanical performance simulations. A combined analysis of statics and transient dynamics is carried out for the front-end fixture assembly. Under the extreme condition of carrying a 101.69-kg oil pipe (with an equivalent load of 1200 N), finite element calculations show that the stress concentration of the 45-steel fixture is mainly distributed in the pipe-wall contact area (as shown in Figure 5). According to the stress theory of tension and compression rods in material mechanics:

$$\sigma = FA \tag{4}$$

Where: σ is the stress, F is the applied external force, and A is the effective load- bearing cross-sectional area.

Through theoretical calculations and verification of the finite element results, the peak stress in this area reaches 76.58 MPa, corresponding to a safety factor of 3.36, while the stress level of the small force-transmitting connecting rod is only 2.2 MPa. Under the simulated 10g impact load condition, the overall maximum stress of the fixture arm is 28.13 MPa, significantly lower than the 355 MPa yield strength standard of 45 steel material[9]. This indicates that the structure has good dynamic load-bearing capacity.

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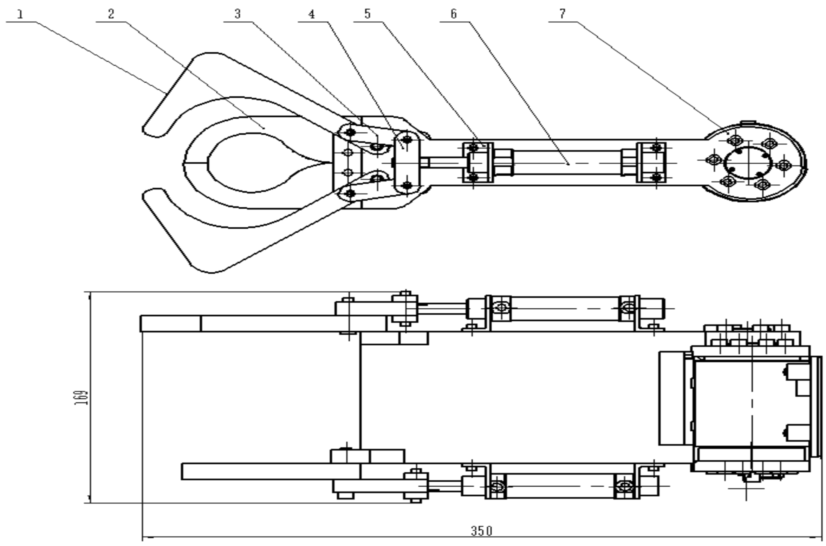

Figure 5. Two-dimensional diagram of fixture mechanical arm

(1). Positioning fixture (2). Gripping fixture (3). Small connecting rod (4). Connecting rod earring (5). Hydraulic cylinder bracket (6). Integral hydraulic cylinder (7). Swinging hydraulic cylinder

For the rotating arm system, a bending stress check analysis is conducted based on the theoretical model of the cantilever beam. The finite element method is employed to simulate the mechanical properties of the secondary arm made of Q235 steel (as shown in Figure 5). The results indicate that under a 2200-N load condition, the maximum stress value is 36.78 MPa, and the corresponding safety factor reaches 4.2. According to the classic cantilever beam bending stress formula:

$$\sigma = IMy \tag{5}$$

Where: M is the bending moment, y is the vertical distance from the target stress point to the neutral axis, and I is the moment of inertia of the cross-section.

By optimizing the cross-sectional geometric parameters, the stress concentration factor of the dangerous cross-section is successfully reduced from 1.84 to 1.05, a 42% decrease[6]. For the lifting device, the buckling analysis reveals that its critical buckling load factor K= 4.8, which is significantly higher than the dynamic stability threshold of 1.5 specified in the API 7K standard, thus meeting the requirements of industry specifications[11]. The strength calculation results of the key components are presented in Table 2. Based on Miner's linear cumulative damage theory, we predicted the fatigue life of the rotating arm under cyclic loading. The calculation results indicate that after 10^6 cycles of loading, the cumulative damage value reaches 0.23 (as shown in Figure 6). From this, we can infer that the theoretical service life of the rotating arm can exceed 107 cycles.

Table 2. Statistical Calculation of Strength of Key Components

Component	Material	Load Condition	Calculated Stress σ(MPa)	Allowable Stress σ	Factor of Safety n
45 Steel Fixture	45 steel	1200N	76.58	105.6	3.36
Q235 Secondary Arm	Q235	2200N	36.78	157	4.2
Lifting Device	Q235	6290N	57.84	157	2.71

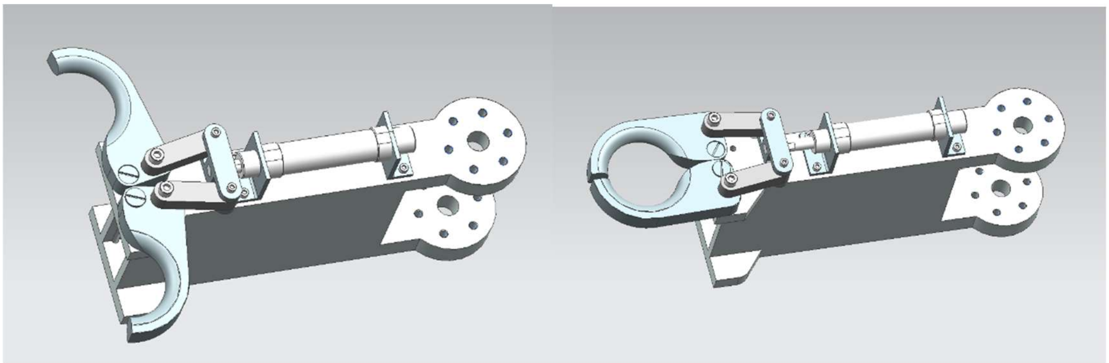

Figure 6. Fixture Opening and Closing

3.3 Control System and Service Performance

A three-closed-loop control system architecture is constructed based on the Siemens S7-1200 PLC (as shown in Figure 2). In the position control loop, a 17-bit resolution absolute encoder is used as the pose feedback element. The PID control algorithm (proportional coefficient Kp=1.2), integral time Ti=0.05s) is employed to achieve trajectory tracking, keeping the position error effectively within ±5mm. For the hydraulic synchronous control loop, a proportional valve is utilized to precisely adjust the displacement of the double hydraulic cylinders. By combining with the oil temperature fluctuation compensation algorithm described in Reference, the synchronization accuracy can reach the 0.5mm level[12]. In the safety protection loop,a high-frequency pressure sensor (sampling frequency 1kHz) is installed to monitor the operating clamping force in real time. Once the detected value exceeds 10% of the set threshold, an emergency braking mechanism with a response time of less than 0.1s will be triggered.

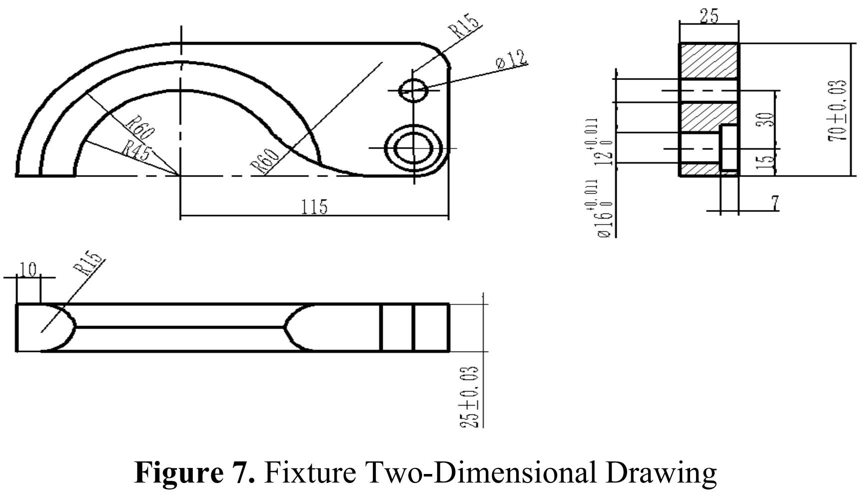

Figure 7. Fixture Two-Dimensional Drawing

The results of the co-simulation analysis based on ADAMS and AMESim (as shown in Figure 2) indicate that under the 5Hz vibration condition, the standard deviation of the system's positioning error is 0.8mm, and the maximum stress amplitude of the transient shock response reaches 109MPa, meeting the requirements of the API 8C dynamic load specification.

An on-site test was conducted on the DT-40 workover rig platform in the oilfield. After verification according to the ISO 9286 standard, the standard deviation of the system's positioning accuracy remains stable at 0.8mm.The measured data show that the system significantly reduces manual intervention. The manual intervention rate in wellhead operations has decreased by 82%. The efficiency of tubing tripping operations has been greatly enhanced, with the tripping time for a single tubing shortened from 4.5 minutes to 2.1 minutes. Compared with traditional operating devices, the system's trajectory control accuracy has been significantly improved. The shaking amplitude has been

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reduced from ±50mm to ±1.2mm, a reduction rate of 97.6%. The working radius has been extended from 0.5m to 1.5m, achieving an effective extension of 200%. The comparison of the control system's performance indicators is shown in Table 3.

Table 3. Comparison of the control system's performance indicators

Control Dimension	| Traditional Manual Operation	| This Design Control System
Positioning Accuracy	±50mm	±0.8mm(an increase of 98.4%)
Response Time	＞2s	0.1s（an increase of 95%）
Hydraulic Synchronization Difference	＞5mm	0.5mm（a decrease of 90%）

3.4 Engineering Verification and Performance Comparison

A total of 200 consecutive engineering tests were conducted (as shown in Figure 8). The measured data indicate that, compared with traditional suspension fixtures, the new pusher-arm system significantly shortens the single-tubing tripping operation time from 4.5±0.8 minutes to 2.1±0.3 minutes, boosting the operation efficiency by up to 53%. Moreover, the frequency of manual intervention is reduced by 82%. In terms of trajectory control performance, the trajectory fluctuation range has been optimized from ±50mm to ±1.2mm, enhancing the trajectory stability by 97.6%. The positioning repeatability accuracy reaches ±0.8mm. The clamping force fluctuation coefficient has dropped to 7.2%, a 64% reduction compared with traditional devices.

After undergoing fatigue life tests, the key components still maintain their structural integrity after enduring 10^7 cyclic loads. The operating failure rate is 0.23 times per thousand hours, significantly lower than the industry average of 1.5 times per thousand hours. The key performance parameters are presented in Table 4:

Table 4. Engineering verification results of the key performance parameters

Indicator	Traditional Suspension Clamp	This Design Push Arm	Lifting Amplitude
Single Root Hoisting and Lowering Time	4.5min	2.1min	53%
Manual Intervention Frequency	3-5 persons	0.6 person (a reduction of 82%)	-
Annual Maintenance Cost	620,000 yuan	250,000 yuan (a reduction of 370,000 yuan) 60%	60%
Economic Benefit	-	1,260,000 yuan/year	-

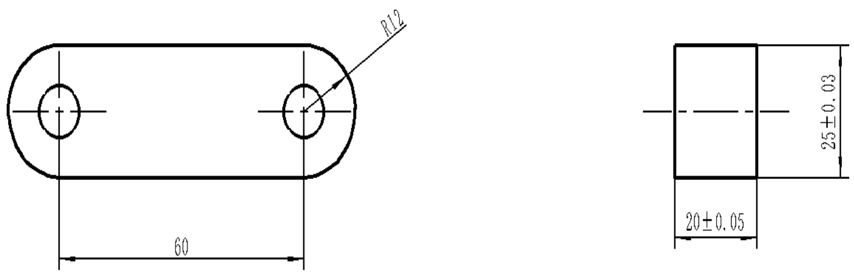

Figure 8. Small Connecting Rod Two-Dimensional Drawing

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4. Conclusion

This research has achieved three core breakthroughs in the aspect of structural innovation and system verification, they are:

(1) A pusher-arm architecture integrating lifting, rotating, and grabbing functions was pioneered. Its working radius has been extended to 1.5 m (a 200% increase compared with traditional suspension clamps), and the positioning accuracy has reached ±5 mm (a 10-fold increase compared with the traditional ±50mm), completely eliminating the instability of the oil-pipe conveying trajectory.

(2) The key components have sufficient stress safety margins under an ultimate load of 1500 N: the 45- steel clamp has a stress of 76.58 MPa (safety factor of 3.36), the Q235 rotating arm has a stress of < 37 MPa (safety factor of 4.2), and the lifting mechanism has a stress of < 58 MPa, meeting the API Spec 8C strength specification.

(3) Engineering applications have confirmed that after integrating the system into a 40-ton workover rig, 47 minutes of working time can be saved per well, and the operation efficiency is increased by 53%, providing a reliable technical paradigm for the automation transformation of China's oilfields.

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