

Axial Impact Analysis of Torsion Impactor Based on Water Strike Effect

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Abstract: The stick-slip vibration phenomenon that occurs during the drilling process not only reduces the drilling speed, but also affects the performance of the drill pipe and the service life of the drill bit. In response to the problem of stick-slip vibration, a torsional impactor has been developed. The tool, through its internal throttle action, will produce a sudden change in the mass flow of fluid in the central tube and thus produce a water strike phenomenon, and the change in the axial force of the torsional impactor caused by the water strike effect can cope with the stick-slip vibration that occurs during drilling as well as increase the drilling efficiency. In this paper, the axial impact capacity of the tool is investigated based on its water impact effect. CFD simulations were used to determine the axial impact capacity of the torsional impactor at different drilling fluid flow rates, and the maximum equivalent force of the central tube under the water impact effect was analyzed and strength checks were performed. The research results show that: two axial vibrations occur in the center tube within half a working cycle; As the drilling fluid flow rate increased from 24L/s to 31L/s, the axial impact force of the torsion impactor increased from 32506N to 43189N; the maximum equivalent force of the center tube is 106.59 MPa, which meets the impact strength requirements. Finally, it was verified through field tests that the water impact effect generated inside the torsional impactor can effectively solve the stick-slip vibration problem and improve the rock-breaking efficiency under different drilling fluid flow rates.

Keywords: Torque Impactor, Water Strike Effect, Bi-directional fluid-solid coupling, Axial impact.

1. Introduction

During the development of deep and ultra-deep wells, as the drilling depth increases, the abrasiveness of the stratigraphic rocks increases, reducing the drilling rate [1-3]. In the process of drilling deep wells and ultra-deep wells, stick-slip vibration is the vibration caused by excessive torque of the drill string when the drill bit cannot drill in hard formations or abrasive layers. Therefore, the phenomenon of stick-slip vibration during drilling cannot be ignored [4-9]. Stick-slip vibration not only affects the service performance of the drill pipe and the service life of the drill bit, but also leads to the loss of drilling engineering [10-13]. Hard rock is characterized by low shear strength, high brittleness, and low impact resistance. Therefore, a certain axial pressure is applied to the drill bit on the basis of WOB, and the stress formed by dynamic pressure and static pressure can effectively break the rock [14]. Changes in the internal flow path of the torsional impactor can lead to transient changes in fluid flow within the tool, which combined with the water strike phenomenon in the pipeline fluid can achieve axial impact and improve rock breaking efficiency.

Realizing "drill string vibration" during horizontal well drilling is of great significance for reducing drilling friction, controlling wellbore trajectory, ensuring well quality, and increasing penetration rate. Therefore, realizing "drill string axial vibration" has become the goal of the drilling industry [15]. Liu Yongsheng [16] established the water hammer equation of the vibration drag reduction tool based on the water hammer effect, and obtained the fluid pressure and velocity distribution in the coiled tubing with the oscillating drag reducer, as well as the axial force and radial force generated by the water hammer on the coiled tubing. The

results show that when the fluid passes through the oscillator, the change of fluid velocity produces instantaneous axial tension. Fu Jianhong [17] proposed a theoretical relationship between the axial vibration velocity and the friction coefficient of a hydraulic oscillator. According to the principle of axial vibration drag reduction, a dynamic analysis model of the whole well drill string with hydraulic oscillator was established, and the influence of the installation position, maximum vibration force and vibration frequency of the hydraulic oscillator on drag reduction was simulated. Jialin Tian [18] proposed a new type of downhole vibration tool in combination with downhole conditions, analyzed the axial vibration of the drill string, established a dynamic analysis model for the axial vibration of the horizontal well drill string, and determined the variation law of the axial force. Tian Jialin [19] analyzed the mechanical characteristics of the negative pressure pulse hydraulic oscillator. The results show that when the fluid flow input into the tool is constant, the larger the diameter of the radial nozzle of the valve shaft system, the greater the pressure drop of the tool and the generated water hammer pressure, and the greater the impact force of the axial force generated. Yin Yiyong [20] developed a downhole screw motor two-way vibration cementing tool, analyzed the vibration generated by the cement slurry during the cementing process, and obtained the axial vibration frequency of the tool and the water hammer pressure formula. Based on the water hammer vibration effect, this paper establishes the water hammer mathematical model of the torsion impactor, analyzes the variation of the axial force with time under a fixed flow rate, and fits the change curve of the maximum axial force under different drilling fluid flow conditions.

2. Methods

The focus of this paper is the water hammer analysis of the torsion impactor, and the test is carried out to verify the analysis results. This research is carried out through the following series of steps.

1) First, a torsional impactor is designed for the stick-slip vibration phenomenon that occurs during drilling. Based on the working characteristics of this torsional impactor, a mathematical model of fluid-solid coupling water hammer is established from the perspective of axial force analysis.

2) Secondly, establish a finite element model and use CFD simulation to determine the axial impact capacity of the torsion impactor under different drilling fluid flow rates.

3) Then, check the strength of the central tube that generates axial vibration to determine whether it can meet the requirements for normal work.

4) Finally, the on-site test of the torsion impactor prototype was carried out and the analysis results were compared and verified, and the follow-up research direction of the torsion impactor was proposed.

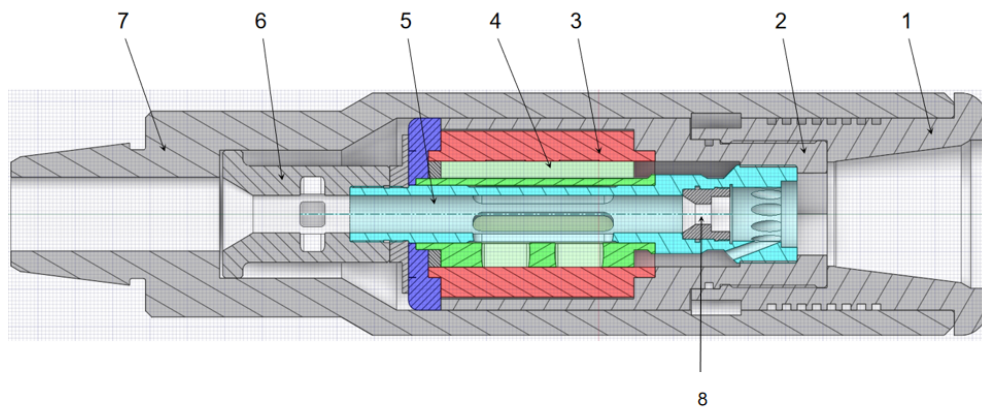
3. The Internal Structure and Working Principle of The Torsion Impactor

The torsion impactor consists of a lower joint, a valve body, a hydraulic hammer, a reversing valve, a central tube, an upper joint, an upper joint shell, and a throttle, as shown in Figure 1.

The upper joint shell of the torsion impactor is used for connecting with the drill pipe, and the lower joint is used for fixed connection with the drill bit. After the upper and lower joints of the torsion impactor are connected and fixed with the drill pipe and the drill bit, the internal space is mainly used

for the mutual cooperation between the parts to realize the main function of the tool. The orifice plays the role of throttling and reducing pressure, so that a high-pressure chamber and a low-pressure chamber appear inside the tool, which is a key component for the tool to realize its main function. In the whole twist punch torsion impactor work cycle, due to the pressure difference between the high and low pressure chamber to push the hydraulic hammer and reversing valve to do accelerated movement, this time the flow into the impact component will also gradually increase, and after the collision occurs, the flow into the impact component will be transient changes, based on the principle of water strikes, the torsion impactor can provide four times axial vibration. In the event of a water strike situation, the axial vibration will be transmitted to the center pipe through the orifice, then to the valve body, and finally to the lower joint. Due to the influence of drilling fluid displacement, the rotational speed driven by the pressure drop generated by the orifice is very fast, so a high-frequency external force can be applied to the drill bit.

Traditional roller cone bits and PDC bits often have a certain degree of "stick-slip-sticking" and insufficient drilling efficiency when drilling, which will cause greater wear and tear on the bit itself and affect the working life of the bit. However, the torsional impactor provides additional circumferential torque and axial load to the drill itself, and the water impact effect enables the tool to have axial impact, increasing the axial force of the tool, increasing the mechanical drilling speed of the drill and improving the rock breaking efficiency. Even when working in relatively hard formations, its drilling efficiency is much higher than that of conventional drilling, which significantly reduces the number of trips, saves labor costs, and improves the economy of the entire drilling project.



1-Lower connector; 2-Valve body; 3-Hydraulic hammer; 4-Reversing valve; 5-Central tube; 6-Upper connector; 7-Upper Connector Housing; 8-Throttle

Figure 1. Overall structure diagram of torsion impactor

4. Water Hammer Analysis

On the premise that the solid structure and the water domain are coupled, the water hammer wave theory is a combination of fluid transient theory and structural dynamics theory [21]. The water hammer form of pipeline fluid-solid coupling mainly consists of friction coupling, Poisson coupling and bond coupling. Due to the working characteristics of the torsion impactor studied in this paper, there is a sudden change in flow at the upstream part of the orifice, and there will be a pressure difference at the transition

surface of the orifice. Therefore, the flow-solid coupling form designed in this paper mainly consists of a combination of bond coupling and Poisson coupling.

4.1. Water strike mathematical model

Water strike is a special unsteady flow phenomenon caused by rapid changes in the internal flow of the system in a pressurized hydraulic system. Li Shuhui [22] was the first to propose the concept of closed equations on water strike calculation, that is, directly through the one-dimensional non-constant fluid equation of motion, continuity equation, liquid

elasticity equation and pipe wall elasticity equation to form a closed set of equations for water strike calculation. The core of the fluid-solid coupling water hammer theory is that the unsteady flow of the fluid induces the motion of the solid structure, and the motion of the solid structure acts on the fluid in turn, changing the motion state of the fluid, that is, it is necessary to consider the coupling vibration between the

solid structure and the fluid at the same time. Therefore, on the basis of the closed water hammer calculation equations, combined with the solid structure motion equation and continuity equation, the mathematical model of fluid-solid coupling is given.

4.1.1. Differential equations of fluid motion

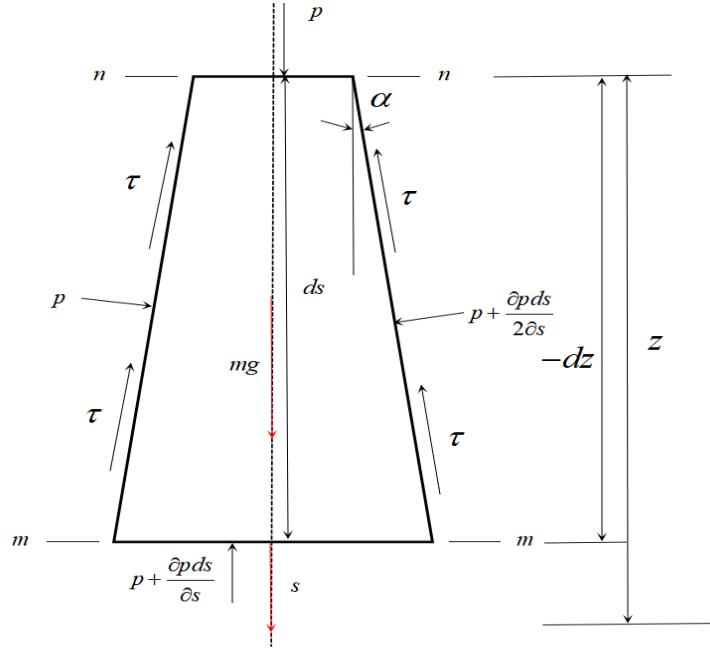


Figure 2. Force diagram of fluid microelement

Figure 2 shows the force on the micro-elements of the fluid. Using the microelement method, combined with Newton's second law, the differential equation of fluid motion is obtained:

$$\frac{\partial p}{\rho \partial s} + \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial s} + g + \frac{\tau x}{\rho A} = 0 \quad (1)$$

4.1.2. 3.1.2 Fluid continuity equation

Using the principle of mass conservation, the continuity equation of the unsteady total flow can be derived directly, and the general form of the unsteady flow continuity equation is:

$$\frac{\partial(\rho v A)}{\partial s} + \frac{\partial(\rho A)}{\partial t} = 0 \quad (2)$$

In the process of water strike propagation, the pressure, cross-sectional area, fluid density and cross-sectional flow velocity are expanded to the time and displacement functions, and the following is obtained:

$$A v \frac{\partial(\rho)}{\partial s} + \rho v \frac{\partial(A)}{\partial s} + \rho A \frac{\partial(v)}{\partial s} + \rho \frac{\partial(A)}{\partial t} + A \frac{\partial(\rho)}{\partial t} = 0 \quad (3)$$

Due to:

$$\begin{aligned} \frac{\partial(A)}{\partial t} &= \frac{\partial(A)}{\partial t} - v \frac{\partial(A)}{\partial s} \\ \frac{\partial(\rho)}{\partial t} &= \frac{\partial(\rho)}{\partial t} - v \frac{\partial(\rho)}{\partial s} \end{aligned} \quad (4)$$

Bring formula (4) into formula (3), after processing, we get:

$$\frac{dA}{Adt} + \frac{d\rho}{\rho dt} + \frac{\partial v}{\partial s} = 0 \quad (5)$$

Introducing the fluid state equation $\frac{d\rho}{\rho} = \frac{dp}{K}$, where K represents the fluid elastic modulus. The relational expression of cross-sectional area with time is:

$$\frac{dA}{Adt} = \frac{2R}{E\delta} \left(\frac{dp}{dt} - \frac{\mu dF}{2Adt} \right) \quad (6)$$

Putting the state equation and cross-sectional area equation into equation (5), the fluid continuity equation can be obtained as:

$$\frac{2R}{E\delta} \left(\frac{dp}{dt} - \frac{\mu dF}{2Adt} \right) + \frac{dp}{Kdt} + \frac{\partial v}{\partial s} = 0 \quad (7)$$

4.1.3. Pipeline equations of motion

Assuming that the influence of bending, shear deformation and section rotation on the pipe motion is not considered, the pipe is a horizontal pipe, and the same simplification as the fluid equation is made, the motion equation of the pipe can be obtained as:

$$g - \frac{\partial \sigma_z}{\partial z \rho_1} - \frac{\pi D \rho_1 v^2}{8 \rho_1 A_1} = \frac{\partial^2 U}{\partial t^2} \quad (8)$$

Among them: σ_z — Piping Axial Stress ,MPa;

D — Pipe outer surface diameter, m;

v — Fluid motion speed, m/s;

U — Pipeline movement speed, m/s.

4.1.4. Pipeline continuity equation

According to Hooke's law, when a metal material is stressed, there is a linear relationship between stress and strain, and the axial force of the pipeline is generated by the pipeline under the action of axial tension and pulsating force, The initial strain ε_{z0} induced by the axial tension F_0 and the generation of the axial strain ε_z induced by the pulsating force [23], the axial balance equation is:

$$F_1 = EA\varepsilon_z + F_0 \quad (9)$$

From the above formula, the following relationship exists:

$$\sigma_z = E \frac{\partial U}{\partial z} + \mu \sigma_0 \quad (10)$$

From the thin-wall simple hoop tension formula, we can know:

$$\begin{aligned} \sigma_0 &= \frac{pD}{2s} \\ \sigma_h &= \frac{pD}{4s} \end{aligned} \quad (11)$$

British physicist Thomas Young gave the wave velocity formula for incompressible fluid considering the influence of pipe elasticity as:

$$c = \sqrt{\frac{Es}{\rho_1 D}} \quad (12)$$

Put equations (9)-(11) into equation (12), and derive its derivative with respect to time to obtain the pipeline continuity equation:

$$\frac{\partial^2 U}{\partial t \partial z} + \frac{\mu \partial p}{2 \rho_1 c^2 \partial t} - \frac{\partial \sigma_z}{E \partial t} = 0 \quad (13)$$

The mathematical model of fluid-solid coupling is established based on the above four equations, and the calculation principle is explained by establishing the mathematical model of fluid-solid coupling water hammer. Next, the numerical simulation of the fluid-solid coupling water hammer of the torsion impactor will be carried out based on this.

4.2. Numerical simulation

After the reversing valve collides with the hydraulic hammer, the next stage of hydraulic hammer movement has just started, the mass flow flowing into the impact component decreases instantaneously, the mass flow in the central tube increases instantaneously, and water hammer occurs at the position of the orifice, causing the central tube vibrates axially. A two-way fluid-structure coupling method is used to analyze the axial vibration force generated by the sudden change of fluid in the central tube.

4.2.1. Fluent model building

According to the working principle of the torsion impactor, where the appearance of high and low pressure chambers is determined mainly through the outflow branch of the center tube and the upper joint and the downstream of the throttle port, so the finite element model here merges the upper joint and the center tube. Ansys-Spaceclaim module was used to process the model, and the center tube and upper joint SolidWorks models were imported into Spaceclaim to merge the two entities, and then the flow path was extracted. Then use the mesh module to divide the grid. Since Fluent and Transient structures are needed for bidirectional fluid-solid coupling analysis, an encrypted grid expansion layer is set at the fluid-solid interface (excess ratio 0.2, maximum number of layers 5, growth rate 1.2), And set the coupling surface wall in the mesh model to transmit the pressure load. The specific grid model is shown in Figure 3, and the number of grid cells in the model is 2104995.

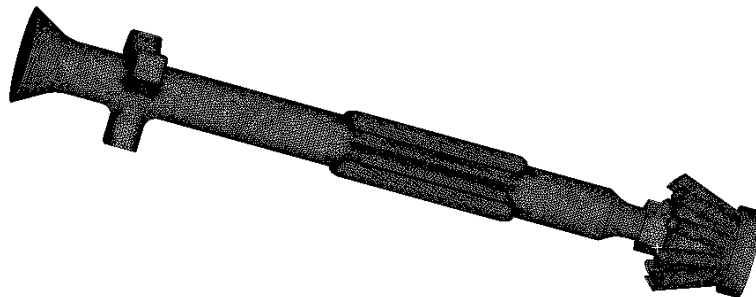


Figure 3. The mesh model of the center pipe and the upper connector flow channel

4.2.2. Transient structure model establishment

In Fluent, set the turbulent flow model to the RNG model,

select the standard wall function as the near wall function, select liquid water as the material, and set the boundary

conditions: set the inflow mass flow inlet (mass flow respectively select 24L/s, 26L/s, 27L/s, 29L/s, 31L/s). Since the flow channel mesh reconstruction is involved in the two-way fluid-solid coupling, set the system coupling surface wall in the dynamic mesh setting (select smoothing and mesh reconstruction, and set the height of the reconstruction unit to 1mm). Mesh the combined entity of the central pipe and the upper joint (subsequently referred to as the central pipe entity) through the mesh module. In order to correspond to the mesh density of the Fluent model and ensure the analysis accuracy, set the overall mesh element size to 2mm, and the solid model The mesh of the middle coupling surface is dense, and its size is set to 1mm. The specific grid model of the transient

structure is shown in Figure 4, and the number of grid cells in the model is 1313607. Since the center pipe and the upper joint do not need to withstand high-frequency high-torque collisions, the transient structural material is set to 42CrMo. Set the solid surface in contact with the Fluent coupling surface wall as a fluid-solid interface to transmit fluid pressure. Referring to the Fluent step size and analysis time, the same settings are made for the transient structure, and the large deformation of the structure is turned on. The amplitude attenuation coefficient is selected for moderate velocity dynamics. Finally, the displacement constraint is defined according to the actual assembly constraint of the torsional impactor.



Figure 4. Solid mesh model of central pipe and upper joint

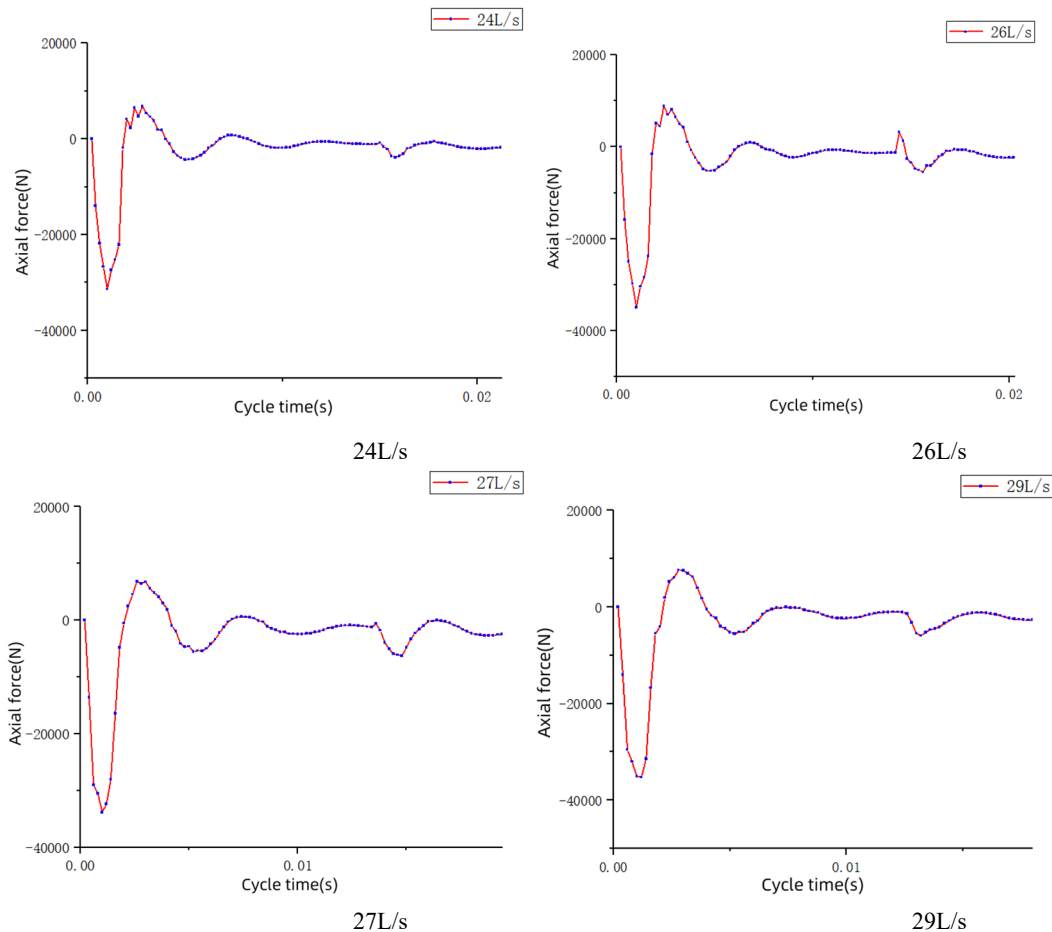
4.2.3. Defining system coupling

Coupling data is transmitted bidirectionally on the interface, and the flow field equation and the structural equation are solved independently in turn, and then the results obtained at each time step are added to the field of the other party in the form of loads. This type of coupling is applied to the structure to generate Large deformations have a non-negligible effect on the fluid. In the system settings, synchronize the time step and analysis time in Fluent and transient structures, and set

the data transfer at the coupled surface wall and fluid-solid interface in both.

4.3. Simulation result analysis

Different drilling fluid flow rates (24L / s, 26L / s, 27L / s, 29L / s, 31L / s) were set at the inlet of the central pipe flow channel for analysis, and the axial force with time under different drilling fluid flow conditions was obtained, as shown in Fig.5.



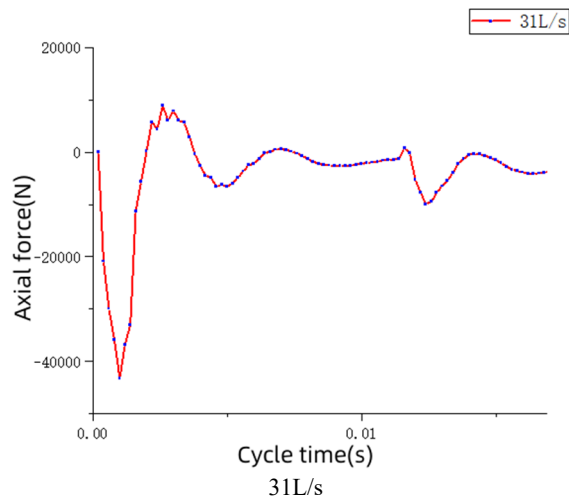


Figure 5. The change curve of axial force with the change of drilling fluid flow rate.

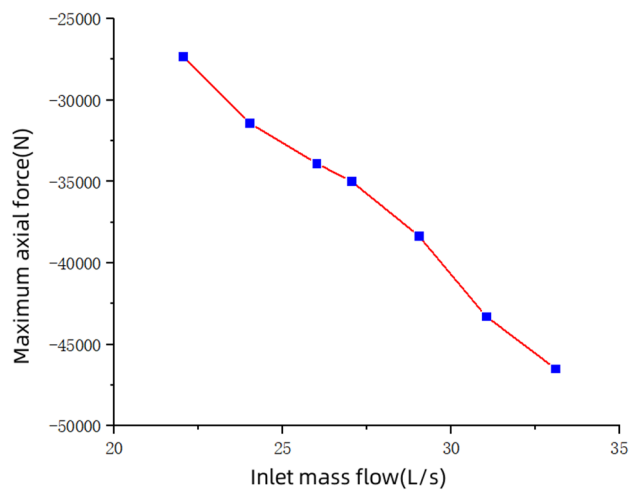


Figure 6. Variation curves of the maximum axial force of the center pipe under different drilling fluid flow rates

When the torsion impactor is working, the drilling fluid first drives the hydraulic hammer and the reversing valve to rotate together, and then drives the reversing valve to rotate separately. During the alternating process of the two, the fluid mass flow rate in the center pipe will change abruptly. It can be seen from Figure 4 that the central pipe will vibrate twice in the 1/2 cycle, and after the reversing valve collides, the axial force when the hydraulic hammer starts to rotate is greater, and because the pressure wave transmission takes time, so Axial vibrations always appear after a collision. Since the direction of the axial force on the displacement constraint surface is opposite to the direction of the axial force transmitted by the actual central tube, the direction of the axial force is negative. With the increase of the drilling fluid flow rate, the axial force of the center pipe always shows an

increasing trend, as shown in Fig. 6.

5. Central Tube Strength Check

The center tube vibrates axially during the working process of the torsion impactor, so strength checking is required to determine whether it meets the requirements of the torsion impactor. As shown in Figure 7, the equivalent stress is mainly concentrated at the three-way outlet of the upper joint and the axial fixation of the upper joint. The equivalent stress analysis of the center pipe was carried out under different drilling fluid flow rates, and the curve of the maximum equivalent stress on the center pipe with time was obtained as shown in Fig. 7.

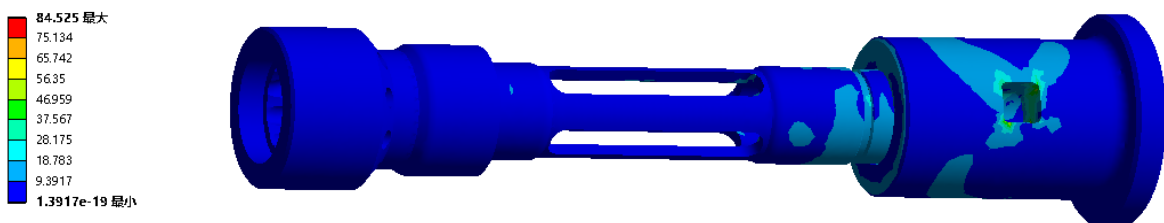


Figure 7. Cloud map of the equivalent stress of the central pipe under the flow rate of 27L/s drilling fluid

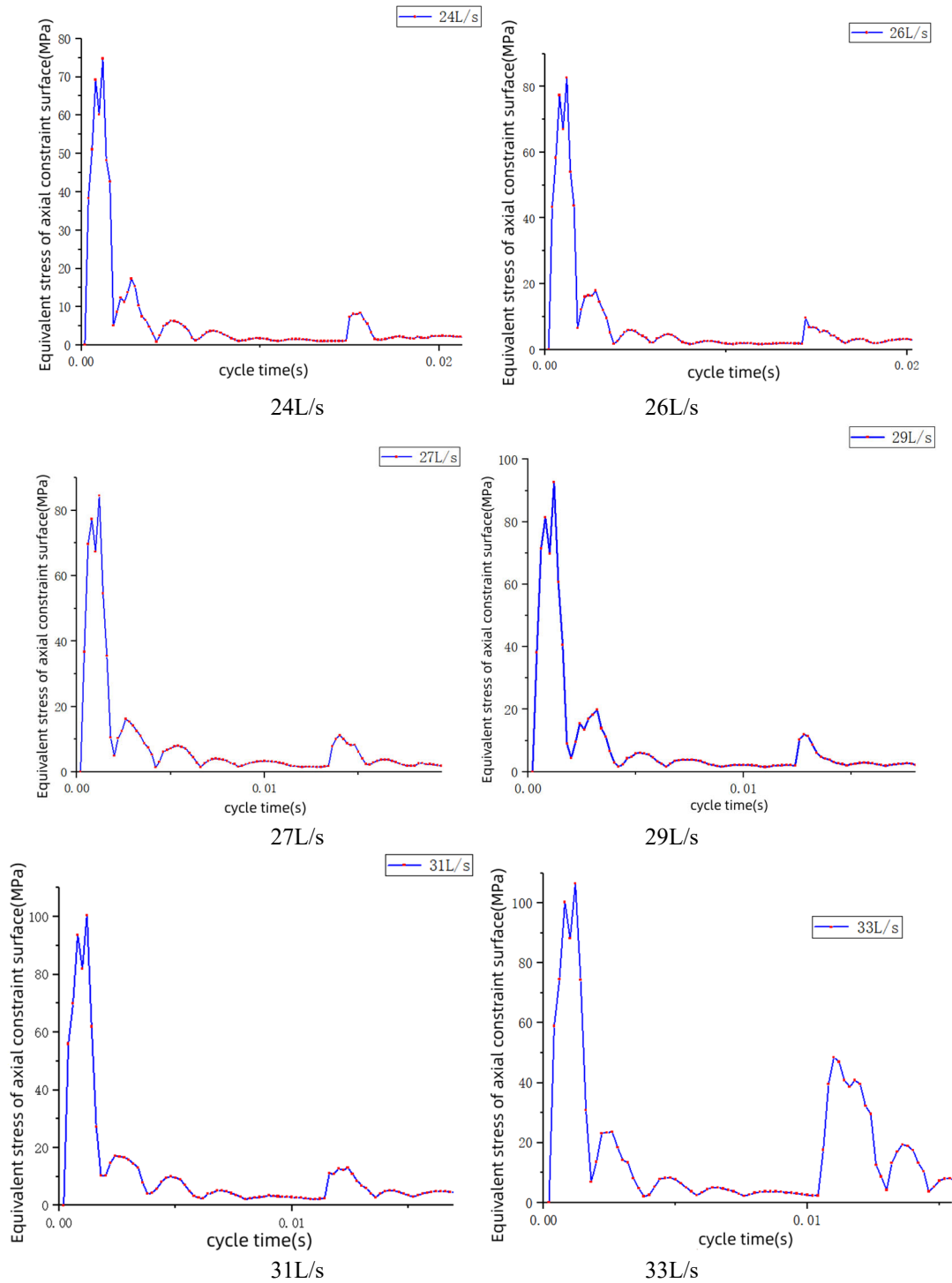


Figure 8. Curves of the maximum equivalent stress of the center pipe versus time under different drilling fluid flows.

As shown in Figure 8, there are two axial vibrations in the central tube, where the maximum stress occurs after the hydraulic hammer starts to rotate. The maximum equivalent stress of the center pipe increases with the increase of the drilling fluid flow rate, and the maximum equivalent stress corresponds to the drilling fluid flow rate of 33L/s, and the maximum equivalent stress is 106.59MPa. Since the material of the central tube is 42CrMo, the yield strength of the material is 930MPa. It can be judged that the torsion impactor can meet the required strength requirements when it is subjected to water hammer.

6. Results and Discussion

Aiming at the problem of stick-slip vibration in the current drilling process, this paper establishes a fluid-solid coupling mathematical model and a central pipe fluid-solid coupling analysis model based on the working characteristics of the torsional impactor from the perspective of improving the axial impact capacity of the tool. With the help of ANSYS software, combined with the two-way fluid-solid coupling method, the ability of the torsion impactor to transmit axial load was analyzed, and the relationship between the inlet mass flow rate and the axial load was obtained. That is, when the drilling fluid flow rate increases from 24 L/s to 31 L/s, the axial

impact force of the torsion impactor increases from 32106N to 43189N. At the same time, the strength of the center pipe is checked on the basis of two-way fluid-solid coupling. The maximum equivalent stress of the central tube is 106.59MPa, which is much smaller than the yield strength of the central tube, which can meet the strength requirements of the torsional impactor when it is working.

Driven by the drilling fluid, the tool vibrates in both the circumferential direction and the axial direction, and can realize the combination of torsional impact and axial impact, so as to improve the low efficiency when encountering hard formations during drilling. However, the research in this paper is only aimed at improving the axial impact capacity of the torsion impactor, and subsequent collision analysis can be performed on the hydraulic hammer that transmits torque and the valve body (or reversing valve) to determine whether the impact torque of the tool meets the design requirements. Through the above research, the purpose of this paper is to

make the percussion drilling technology mature and to achieve a wide range of popularization and application.

7. Field Test

This test includes two parts: 1. Torsion impactor ground test. 2. Torsion impactor test well test.

7.1. Ground test

At present, the processing and trial production of the torsion impactor prototype has been completed, as shown in Figure 9. The indoor functional test was carried out on the processed prototype, as shown in Figure 10. This test mainly checks whether the assembly of the torsion impactor is accurate and whether it works normally, so as to ensure that the test work of the torsion impactor test well can be carried out smoothly.



Figure 9. Torsion impactor prototype



Figure 10. Ground test

The test results show that the torsion impactor is working normally without failure. Further on-site tests can be carried out to verify the reliability and stability of the tool, and at the same time verify whether the axial impact force of the torsion

impactor is consistent with the simulation results.

7.2. Test well test

Since the drilling and test wells run into the casing is 95/8

"casing, the maximum outer diameter of the torsion impactor used for testing is 172mm, the length is 6800mm, the diameter of the body is 80mm, the upper end is NC50 box, and the

lower end is NC50 male. The detailed technical parameters are shown in Table 1. shown.

Table 1. Technical parameters of the torsion impactor for drilling and testing tests

| Applicable borehole | length | outer diameter | Salvage OD | Connection buckle type | frequency | Impact torque |
|---------------------|--------|----------------|------------|------------------------|---------------------|---------------|
| 8 ½" | 786mm | 194mm | 165mm | 4-1/2REG | 1000-2400 times/min | > 1000Nm |

After determining the parameters and making preparations, start the pump. The drilling fluid displacement used is 24-31L/s and the density is 1.1-1.2g/cm³. Finally, record the axial force corresponding to the displacement and compare it with the simulation analysis results, and the results are shown in Table 2 below.

Table 2. Torsion Impactor Test Record Form

| Displacement(L/s) | Axial force (test result) | Axial force (CFD analysis result) |
|-------------------|---------------------------|-----------------------------------|
| 24 | 32729N | 32506N |
| 26 | 34513N | 34286N |
| 27 | 35380N | 34548N |
| 29 | 37650N | 36853N |
| 31 | 42853N | 43189N |

By comparing the simulation analysis results with the test results in the above table, it can be seen that the simulation results are basically consistent with the field test results, and the field test shows that: When the displacement is controlled by the orifice, the water hammer effect generated by the central tube inside the torsion impactor can effectively solve the problem of stick-slip vibration when the drill bit is drilling. Increasing the mass flow rate of drilling fluid can provide greater axial force for the torsional impactor, thereby improving rock breaking efficiency.

8. Conclusions

1. According to the working principle of the torsion impactor, a mathematical model of fluid-solid coupling is established through fluid continuity equations and motion equations and solid motion equations and continuity equations.

2. The ability of the torsional impactor to transmit axial load was analyzed by the two-way fluid-solid coupling method, and the axial impact capacity of the torsional impactor was determined under different drilling fluid flow rates, while the maximum equivalent force of the center tube under the action of water strike was analyzed and the strength of the center tube was calibrated.

3. The field test results are consistent with the CFD theoretical analysis results. The results show that under the action of the throttle, the change of the axial force of the torsion impactor based on the water hammer effect can effectively deal with the stick-slip vibration and improve drilling efficiency.

4. The analysis of the axial impact of the torsional impactor lays the foundation for further theoretical and experimental research on the torsional impactor, and also provides a reference for the design and testing of the torsional impactor.

9. List of Abbreviations

CFD: Computational Fluid Dynamics.

10. Declarations

Availability of data and materials

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

YC designed the structure of the torsional impactor, provided technical guidance, and proposed the idea of water hammer effect. He helped write the manuscript. PX built the numerical analysis model, collected and analyzed the data, and was a major contributor to the writing of this article. XL conducted a field trial of the tool and recorded the relevant data. All authors read and approved the final manuscript.

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