

Article

Modeling and Research on Offshore Casing Cutting of Hydraulic Internal Cutting Device

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Abstract: A mechanical model for offshore casing cutting based on the field application of a mechanical cutting device in the South China is presented in this paper. The proposed model includes the calculation of the piston acting on the cutter and the calculation of the cutting torque and wellhead driving torque. The influence of structural parameters on cutting extension distance, cutting torque, wellhead driving torque, and the proportion of cutting torque to wellhead driving torque are analyzed. The required extension distance is related to piston displacement and cutter face angle, the cutter face angle and cutting depth (water depth) have obvious influence on the cutting torque and wellhead driving torque, and the drilling revolution affects the inertia torque and wellhead driving torque. Since the proportion of cutting torque to wellhead driving torque decreased with the increase in the cutting depth, we cannot determine whether the casing cutting is completed based on the sudden decrease in the wellhead driving torque with cutting depths greater than 800 m. The numerical simulation results of the cutting tool cutting the casing show that if the revolution speed is too high, the initial cutting melting of the casing may affect the cutting force, and it is recommended to increase the rake angle as much as possible within a certain range. The field example shows the limitation of judging casing cutting by a sudden drop in torque.

Keywords: casing cutting; mechanical model; parameter analysis; cutting torque; driving torque; judgment failure



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1. Introduction

Since the 1960s, offshore oil production has developed rapidly around the world, and more and more offshore oil production facilities have been established [1,2]. However, the life of offshore oil facilities is usually about 20–50 years [3,4], according to the international practice of offshore oil production and development, and those facilities need to be dismantled if there is no other use for offshore oil and gas facilities after decommissioning [5–9]. At present, the main technologies of offshore casing cutting are blasting cutting, chemical cutting, abrasive jet cutting, drill wire cutting, and mechanical cutting [10]. Mechanical cutting is driven by the hydraulic force of the drilling pump to drive the cutter to rotate and cut the casing, which is widely used for its simple structure, fast operation, good economy, and safety.

For the determination of the completion of casing cutting, judging by the sudden drop in wellhead driving torque is the most common method at present [11]. But the limitation of the method of judging the cutting state through torque is gradually reflected with the gradual development of global oil and gas production from shallow sea to deep sea operation. Dong et al. [12] have pointed out that there is an inaccurate problem in judging casing cutting completion by the torque of an ND-J114 mechanical internal cutter cutting casings. Liu et al. [13] have pointed out that mechanical cutting has the problems of judging cutting state, low cutting efficiency, high vibration, and easy eccentricity when cutting multi-layer casings. Jin et al. [14] have pointed out that mechanical cutting affects the torque greatly when cutting

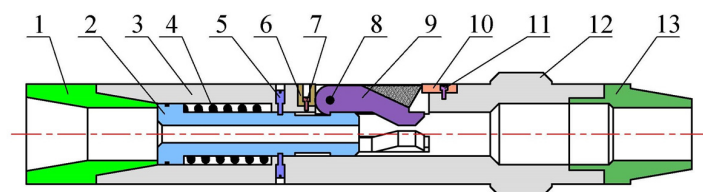
casings in deep water. Mamedov et al. [15] presented a new method to reveal the mechanism of the cutting process. Zhou et al. [16] presented a physical model and mathematical model of casing cutting using a premixing abrasive water jet. Toulouse [17] presented a new casing cutting technology to improve operational efficiency and cut drilling costs. Ivanov and Karapetov [18] presented results of the different subsea assembly cutting methods, applied during the abandonment of VSP offshore wells. Zhou et al. established a dynamic contact force model for the casing cutting process, derived a mathematical model of cutting depth that took into account the influence of time based on the grinding mechanism, and developed a high-performance hydraulic face milling cutter suitable for a 177.8 mm casing [19]. In addition to the problem of the judgment of the casing cutting state and application of different cutting methods, there is little research on the theory of mechanical casing cutting. Since cutting operations are underwater and may be performed on an expensive platform, it is necessary to theoretically analyze the mechanical casing cutting [20].

Based on the previous research by our team [11,21–23], this paper introduces a hydraulically driven mechanical casing cutting device, and combined with the working principle, a theoretical model of mechanical casing cutting is established. We analyzed the relationships between the main structure parameters and the cutting torque, wellhead drive torque, and cutting efficiency. The correctness of the theoretical model was proved by analyzing the practical application in the field, and the limitation of using the sag of wellhead driving torque to judge the casing cutting basis was also explained.

2. Mechanical Casing Cutting Device

2.1. Basic Structure of Mechanical Casing Cutting Device

Figure 1 shows a common type of mechanical casing cutting device that is hydraulically driven [23]. It consists mainly of the upper joint, the piston, the tool body, the return spring, the shear pin, the tool holder, the cutter, the stop block, the centralizer, and the lower joint. The cutting assembly consists of a tool holder, bolt, cutter, and limit block. The cutter shown in Figure 2. It consists of a cutting body and a blade, and the edge of cutting blade is inlaid with cemented carbide to improve the hardness and enhance the cutting performance.



1. upper joint; 2. piston; 3. tool body; 4. return spring; 5. shear pin; 6. tool holder; 7. bolt; 8. pin shaft; 9. cutter; 10. limit block; 11. bolt; 12. centralizer; 13. lower joint.

Figure 1. Mechanical hydraulic internal cutter structure for cutting casings.

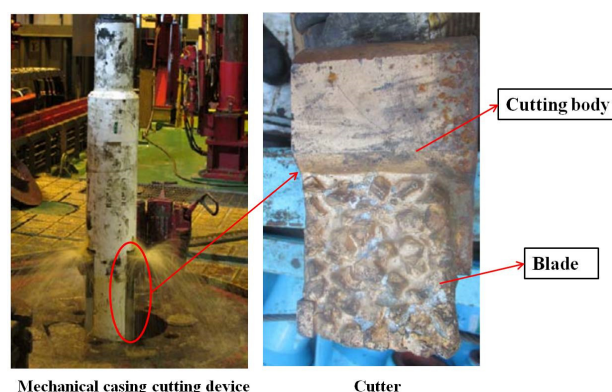


Figure 2. Cutter structure.

2.2. Working Principle

The device is basically consistent with the conventional mechanical cutting process; due to the limitation of the shear pin, the cutter is locked before the pumping and cannot extend beyond the body. When the tool reaches the cutting position, the pump starts and the drilling fluid flows into the drill string, and the shear pin is cut off due to the throttling effect at the upper end of the piston. Then, the piston moves down and the piston will push the cutter to extend, and the rotary table begins to rotate the entire drilling assembly to drive the cutter while cutting the casing. The completion of cutting is judged by monitoring the torque variation of the rotary torque meter during the cutting process. The cutting is considered complete when the wellhead driving torque saws sharply and remains for a period of time. When the cutting is completed, the pump is stopped, the pressure in the drilling string drops, and the piston is reset by the returning spring. Then, the drill string is lifted, and the cutter shrinks into the body. Finally, the assembly of the drilling tools and casing is raised, and the cutting operation is completed. During the operation of the device, it is assumed that the casing is centered along the axis without deformation, and the tool is inserted along the casing axis.

3. The Theory Model of Casing Cutting

The geometric model of the piston and cutter are established in this section and combined with the structure and working principle of the mechanical casing cutting device. The relationship between the cutting radius of cutter tip and piston displacement is analyzed, and the relationship between the maximum torque required by the tool cutting the casing and the minimum torque required by the wellhead turntable is obtained.

3.1. The Relationship between Piston Displacement and Cutting Tool Tip Radius

We simplify the process of moving the piston down and pushing the cutter out and establish a simplified geometric model of the piston and cutter: the coordinate system takes the axis perpendicular to the tool center as the y-axis, the line passing through the central point of the pin axis and perpendicular to the y-axis as x-axis, and point N is the contact point between the piston and cutter, as shown in Figure 3a.

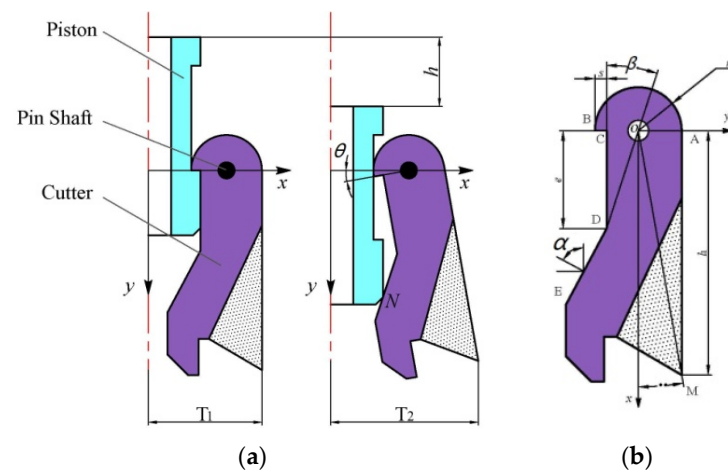


Figure 3. Geometric model of piston and cutter. (a) Geometry of the piston and cutter. (b) Cutter profile.

We can obtain the length y_1 between point N and the x-axis in the process of the casing cutting as follows:

$$y_1 = (r - s) \sin \theta + e \cos \theta + [e \sin \theta + (r - s)(1 - \cos \theta)] \tan(\alpha + \theta) \quad (1)$$

In the formula, r is the radius (arc AOB) of the cutter's rotating seat, s is the length of BC at the upper end of the cutter, θ is the rotating corner of the cutter, e is the length of the straight line CD at the lower part of the cutter, and α is the tangent angle of the end face of the cutter.

The length T_1 between the tip point of the cutter and the axis y at the initial position is the following:

$$T_1 = l_3 + r \quad (2)$$

In the formula, l_3 is the length from the center of the pin axis to the axis y .

During casing cutting, the length T_2 between the tip point of the cutter and the axis y is the following:

$$T_2 = l_3 + l_2 \sin(\gamma + \theta) \quad (3)$$

where l_2 is the length between the tip point of the cutter and the central point of the pin.

With the displacement h of the piston moving downward, the following formula can be obtained:

$$h = (r - s) \sin \theta + e \cos \theta - w + [e \sin \theta + (r - s)(1 - \cos \theta)] \tan(\alpha + \theta) \quad (4)$$

where w is the height of the cutter's rotating seat.

The cutting radius ΔT of the tip point of cutter is the following:

$$\Delta T = l_2 \sin(\gamma + \theta) - r \quad (5)$$

where $l_2 = \sqrt{r^2 + l_1^2}$; l_1 is the length of the straight AM on the cutter; and γ is the angle between the straight line OM and the x-axis on the cutter, $\gamma = \arctan \frac{r}{l_1}$.

According to the above analysis, in order to complete the casing cutting, the extension distance required for the cutter ΔT_r can be calculated from the thickness of the casing, and the desired cutter rotating angle θ_r and the minimum displacement h_r of the piston moving downward can be determined.

$$\Delta T_r \geq D_o - d_r + T_1 = \delta + (d_o - d_r) + T_1 + \chi \quad (6)$$

where D_o is the outer diameter of the casing; d_r is the cutting device's outer diameter; δ is the wall thickness of the casing, $\delta = D_o - d_o$; and d_o is the inner diameter of the casing.

3.2. Calculation of Cutting Torque

During casing cutting, the cutting torque is provided by the turntable. Simplifying the cutter structure, the mechanical model of the cutter is shown in Figure 4. When the casing is cut under an eccentric condition, according to torque balance, we can obtain the following:

$$F_2 \cdot \left(l_2 - \frac{\Delta l}{2} \right) - F_1 \cdot \left(\sqrt{(r - s)^2 + e^2} \cdot \cos\left(\frac{\pi}{2} - \alpha - \beta\right) + \frac{e \cdot \sin \theta + (r - s)(1 - \cos \theta)}{\cos(\alpha + \theta)} \right) = 0 \quad (7)$$

where F_2 is the equivalent force of the casing acting on the cutter; Δl is the length of cutter cutting into the casing; F_1 is the force of the piston acting on a single cutter $F_1 = \frac{F_0 \cdot \cos(\alpha + \theta)}{k}$, k is the number of cutters on the casing cutting device, with the number of cutters being 3 in general; and F_0 is the driving force of the drilling fluid.

Reference [24] shows that the casing cutting can be regarded as the milling of a cemented carbide insert embedded in the cutter body, and each cemented carbide insert can be regarded as a milling cutter tooth. In other words, the process of casing cutting can be approximately considered as the milling process of all cemented carbide blocks in contact with the casing. Therefore, the circular cutting force F_f can be calculated based on the long rod milling model, and the formula is as follows:

$$F_f = 10 \cdot \frac{F_p}{A} \cdot \frac{BtS_zZ}{\pi D} \quad (8)$$

where F_p is the force of the casing acting on a cutter (N); A is the total pressure-bearing area of cemented carbide blocks on a single cutter (mm²); B is cutting width (mm); $t = \Delta l \sin(\gamma + \theta)$

is the cutting depth (mm); S_z is the feed per tooth $S_z = 0.12\sim 0.2$ mm; Z is the number of cemented carbide blocks; and D is the diameter of the tip point of the cutter (mm).

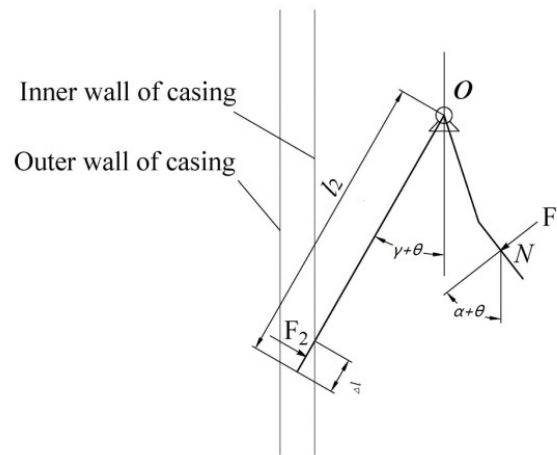


Figure 4. Mechanical model of the cutter.

The maximum cutting torque M_{one} required for one cutter is as follows:

$$M_{one} = f \cdot F_f \cdot R = \frac{5fF_2}{A} \cdot \frac{BtS_zZ}{\pi} \quad (9)$$

where f is the cutting friction coefficient, generally 0.2, which is related to many factors such as pipe wall roughness, cutter tip fragmentation, wear, cutting depth, etc. [25]; R is the radius of the cutter tip of the casing cutter.

The maximum cutting torque M_{all} required for the casing cutting device is as follows:

$$M_{all} = K \cdot f \cdot F_f \cdot R = \frac{5KfF_2}{A} \cdot \frac{BtS_zZ}{\pi} \quad (10)$$

3.3. Calculation of Wellhead Driving Torque

For offshore casing cutting, wellhead torque consists of three parts: cutter cutting torque, seawater resistance moment, and inertia torque generated by the drill string. The formula is expressed as follows:

$$M = M_1(t) + M_2(t) + M_3(t) \quad (11)$$

where M is the wellhead driving torque, $M_1 = M_{all}$ is the cutting torque, M_2 is the resistance torque of seawater, and M_3 is the inertia torque of the casing cutting device and the whole drill string.

The formula for calculating the resistance torque of seawater is as follows:

$$M_2 = 43925.4C\gamma_m D_2^2 L \times 10^{-9} \quad (12)$$

$$\gamma_m = \rho g \quad (13)$$

where C is the deviation coefficient, $C = 1.88 \times 10^{-4}$ in a vertical well; γ_m is seawater gravity; D_2 is the outer diameter of the drill string; L is the cutting depth; ρ is the seawater density; and g is gravity acceleration.

In order to simplify calculations, the whole drill string and the casing cutting device are regarded as an equal section, M_3 , which is expressed as follows:

$$M_3(t) = J\partial \quad (14)$$

where J is the inertia moment; $J = \frac{q_m l (d_2^2 + D_2^2) \times 10^{-6}}{8}$; d_2 is the inner diameter of the drill string; q_m is the quality of the drill string per meter; l is equivalent length of the whole drill string and the casing cutting device; and ∂ is the angular acceleration.

The angular acceleration in the limit case can be expressed as follows:

$$\partial = \frac{\Delta\omega}{\Delta t} = \frac{\omega - 0}{60/n_s} \quad (15)$$

where $\Delta\omega$ is the angle variation within time Δt ; ω is the angular velocity of the drill string, $\omega = 2\pi n/60$, n is the revolution of the drill string; and n_s is the stroke of the pump.

4. The 2D Cutting Simulation Based on Abaqus

4.1. Theoretical Model of Cutting

The cutter mainly cuts the casing wall gradually when cutting the casing. The first factor that determines the effect of casing cutting is the influence of the cutter body and casing material. The basic performance parameters of different materials play a decisive role in the cutting process. In addition, the thickness, speed, and angle of the cutting tip have a greater impact on the cutting process. Zhang et al. conducted three-dimensional modeling and simulation of the cutting process based on Abaqus simulation software (Version 2023), and studied the impact of various cutting factors on cutting temperature using simulation methods [26]. Fredj Montassar et al. predicted the size of the chip cross-section by establishing a geometric model and proposed that appropriate cutting parameters and tool types should be selected to avoid high cutting forces during the cutting operation [27]. Zheng et al. established a predictive model for cutting force analysis and a simplified dynamic chip model. Based on these, they developed and validated a predictive model for cutting dynamics and chatter stability [28]. Ning et al. used the Abaqus simulation software to define a finite element model for CFRP cutting and employed this model to analyze the deformation process of chips and individual fibers [29].

In order to conduct in-depth research on casing cutting, this part combines finite element numerical simulation to further explore the cutting process. Since the metal cutting process is a process of elastic-plastic deformation under high temperature and high strain rate conditions, in order to make the finite element simulation more consistent with the actual processing conditions and obtain more accurate simulation results, a constitutive model that can correctly represent the mechanical behavior of materials is needed in finite element cutting simulation.

At present, the commonly used material constitutive models in research mainly include the Power Law material model, Johnson–Cook material model, Zerilli–Armstrong material model, Follansbee–Kocks material model, etc. This article comprehensively compares the advantages and disadvantages of the above models. Due to the accuracy and simplicity of the Johnson–Cook (JC) constitutive model, it can be applied to material deformation at high strain rates. (A high strain rate indicates that the deformation or strain rate of the material is significant or rapid, and the material may exhibit an increase in strength, a change in ductility, etc.) It also comprehensively considers the effects of thermal hardening, thermal softening, temperature rise, and stress and strain on the material properties of workpieces. It is more consistent with casing cutting. Therefore, the J–C constitutive model is selected for the simulation of the casing cutting process. Its theoretical model is as follows:

$$\sigma = (A + B\bar{\epsilon}^n) \left[1 + C \ln\left(\frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0}\right) \right] \left[1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m \right] \quad (16)$$

In the formula, σ is the material flow stress; $\bar{\epsilon}$ is the equivalent plastic strain; $\dot{\bar{\epsilon}}$ is the equivalent plastic strain rate; $\dot{\bar{\epsilon}}_0$ is the material reference strain rate; and T , T_r , and T_m are the transient temperature, room temperature (20 °C), and material melting point temperature, respectively. The coefficient A is the yield strength, B is the strain hardening

parameter, C is the strain rate hardening parameter, n is the strain hardening index, and m is the thermal softening coefficient. A , B , C , n , and m in Formula (16) are obtained through experiments, and the parameters are shown in Table 1.

Table 1. J-C model parameters of the material.

A/MPa	B/MPa	C	n	m
1150	739	0.014	0.26	1.03

4.2. Simulation Model and Boundary Conditions Based on Abaqus

The actual cutting of the tool is mainly eccentric cutting, that is, the rotation center of the tool is inconsistent with the center of the casing, and the cutting forms a crescent shape. Subsequently, the position is gradually adjusted, and ultimately the entire cross-section of the casing is cut. Based on the actual cutting process, in order to simplify the simulation time and cutting process, the two-dimensional cutting model diagram shown in Figure 5 is established. The properties of the material are assigned to the casing model, and the tool is regarded as a rigid body. The deformation of the tool is ignored during the cutting process, and the Johnson–Cook model is used as the constitutive model of the material. The top and side of the workpiece are fixed during the cutting process.

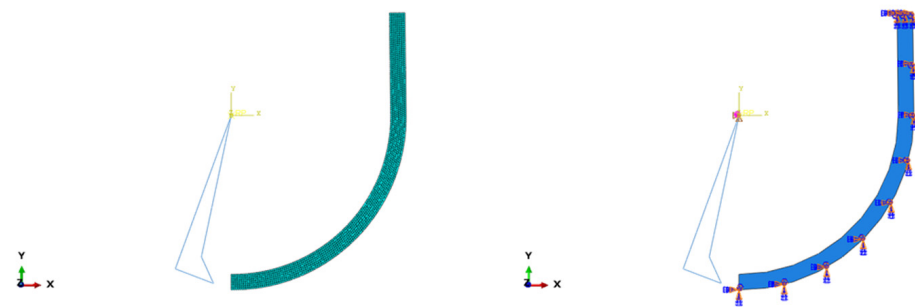


Figure 5. Two-dimensional cutting finite element model.

The quality and quantity of the grid affect the calculation results to some extent. Therefore, a grid independence test is necessary [30].

In the calculation process, the tool model was divided into grid numbers of 408, 852, 1424, and 2370 for grid independence tests. When the number of grids increased from 1424 to 2370, the change rate of the calculation results was 1.59%. In other words, for a number of grids greater than 1424, a further increase in the number of grids had little impact on the calculation results.

Therefore, according to the independence criteria, 1424 grids were selected for subsequent analysis to ensure computational accuracy and speed. The workpiece element type is CPS4R.

4.3. Simulation Analysis and Results Based on Abaqus

On the basis of the above, the influence of tool rotational speed, single cutting thickness, and cutting edge rake angle on the cutting process of casing cutting was studied.

4.3.1. The Influence of Different Tool Rotational Speeds on Cutting Simulation

Referring to the actual cutting speed, the influence of different tool rotational speeds on casing cutting is obtained as shown in Figure 6.

The results of Figure 6 indicate that when the tool cuts at different angles, the maximum cutting equivalent stress of the casing increases with the increase in the tool's rotational speed, and the cutting equivalent stress is approximately proportional to the cutting speed. However, if we carefully observe the entire cutting process, in the initial stage of increasing the cutting speed, the cutting force decreases as the cutting speed increases. This is because at the beginning

of cutting, the cutting temperature is low, and it is easy to form a built-up edge around the cutting edge of the tool, which will cause the cutting force to decrease. When the cutting speed increases to a certain extent, the cutting temperature increases, and the built-up edge disappears with the increase in the cutting temperature. That is, the working rake angle of the tool gradually returns to its original rake angle, so that the cutting force relative to the initial force increases. If we continue to increase the cutting speed, the cutting tool and the contact surface begin to thermally fuse (micro-fusion), which can play a small special lubrication role, reducing friction. At the same time, as the cutting temperature rises, the mechanical properties of workpiece materials decrease, which also causes the cutting force to decrease.

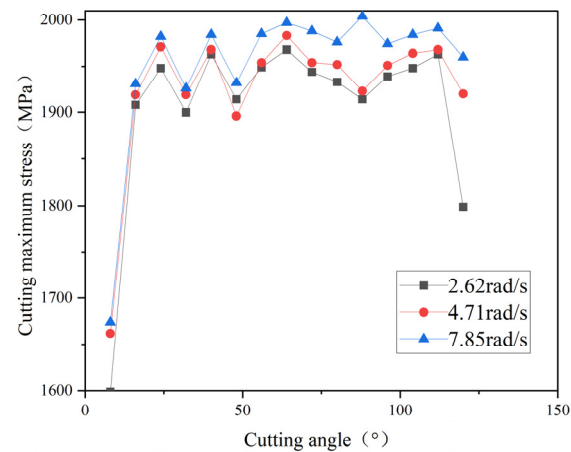


Figure 6. The relationship curve between the maximum cutting equivalent stress and cutting angle at different rotational speeds.

4.3.2. The Impact of Different Cutting Depths on Cutting Simulation

By reasonably setting the single cutting amount, it can protect the tool and also improve the efficiency of casing cutting. Based on the same working condition, when obtaining different cutting depths, the equivalent stress of casing cutting is shown in Figure 7. The results from the above figure lead to the following conclusion: as the single cutting depth increases, the maximum cutting equivalent stress of casing also increases. When the cutting depth increases, the cutting layer area also increases. Since the cutting force per unit area is constant, as the cutting layer area increases, the total cutting force also increases, leading to an increase in the cutting force. Increasing the single cutting thickness can improve the cutting efficiency of the casing, but a too large thickness may cause the bending of the tool and wear on the tool body surface. Therefore, it is necessary to choose the single cutting thickness reasonably in the field.

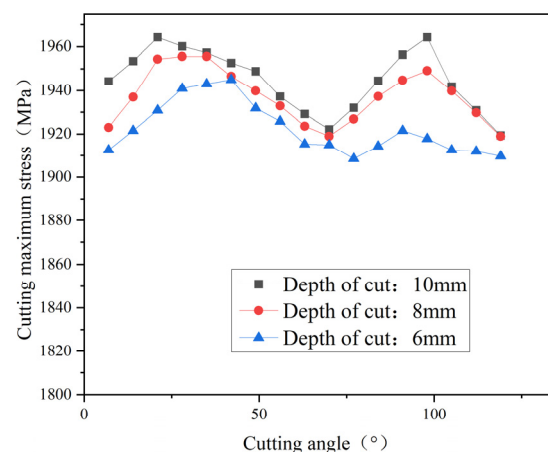


Figure 7. The relationship curve between the maximum cutting equivalent stress and cutting angle at different cutting depths.

4.3.3. The Impact of Different Tool Front Angles on Cutting Simulation

The design and installation of the rake angle is crucial to the cutting efficiency. Under the same conditions, the cutting tubes with different rake angles are shown in Figure 8. It can be seen from the above figure that the cutting force has a certain relationship with the rake angle of the cutting tool (i.e., the angle between the front-end surface of the cutting tool and the base surface of the cutting tool on the main cross-section), which is basically inversely proportional. When cutting plastic materials, the maximum cutting equivalent stress decreases as the rake angle increases within a certain range, since the increase in the rake angle leads to a decrease in the deformation coefficient, thus reducing the cutting force.

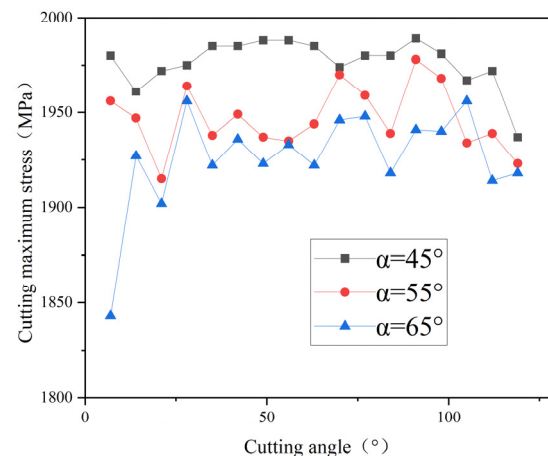


Figure 8. The relationship curve of maximum cutting equivalent stress versus cutting angle for different tool front angles.

4.3.4. Summary of the Chapter

(1) The numerical simulation results show that appropriately increasing the rotation speed can increase the cutting equivalent stress of the cutting tube and accelerate the cutting process, but an excessively high rotation speed can lead to thermal fusion (micro-fusion) at the contact surface between the cutting tool and the cutting tube, reducing the cutting force. (2) Reducing the single cutting depth decreases the cutting layer area. Since the cutting force per unit area is constant, the total cutting force decreases when the cutting layer area decreases, thus reducing the cutting force. (3) To reduce friction and cutting resistance at the front end of the cutting tool, it is recommended to increase the rake angle within a certain range.

5. Analysis of Influencing Factors on the Cutting Efficiency of the Cutting Tool

The cutting force between the cutter and casing, cutting torque, and speed determine the cutting efficiency and cutting quality of offshore casing cutting operations. Tang et al. optimized the structure and shape of the cutting tooth arrangement through LS-DYNA simulation, thereby improving the efficiency of casing cutting [31]. Bondor P et al. studied how cutting speed affects parameters such as cutting force, cutting temperature, tool life, wear mechanisms, and chip formation through finite element simulation [32]. R. N. Bosire et al. utilized the finite element method to model and simulate the machining process of induced residual stress, thereby determining the effects of cutting speed, feed rate, and cutting depth on cutting stress [33]. Based on actual field data from casing cutting, Zhu et al. established a mathematical model between cutting parameters and individual objectives. They conducted equivalent simulation experiments for downhole cutting and verified the reliability of the model [34]. Since the cutting force is mainly determined by the pressure of the fluid acting on the piston, calculating the pressure of the fluid acting on the piston has great significance to the selection of the parameters of the abandoned well operation.

Since the cutting torques M_1 , circular cutting force F_f , and the radius of the cutter tip for casing cutter R are all related to the cutter face angle α , the speed of the drill string, and the depth of water, we chose those above parameters for analysis. The casing cutting example is analyzed by field well LX-X, the outer diameter of the cutting casing is 13-3/8", and main parameters are shown in Table 2. The resulting data are calculated by applying MATLAB software (R2020a) to solve the theoretical model.

Table 2. Basic parameters of 13-3/8' casing cutting.

Parameters	Value	Parameters	Value
d_2/mm	151	f	3.5
D_2/mm	168	A/mm^2	32
$q_m/(\text{Kg}/\text{m})$	122	$n/(\text{r}/\text{min})$	45
K	3	$n_s/(\text{min}^{-1})$	85
$\rho/(\text{kg}/\text{m}^3)$	1025	L/m	850
$g/(\text{N}/\text{Kg})$	9.8	d_0	313
S_z/mm	0.12	D_0	340
Z	12	d_r	298

5.1. The Cutter Face Angle α

The relationship between the extension distance ΔT and the required displacement of the piston h at different cutter face angles α is shown in Figure 9. From the results, we can know that the required displacement h of the piston increases the extension distance ΔT , the displacement h of the piston increases as the angle of the cutter face increases α , and ΔT should reach the same distance.

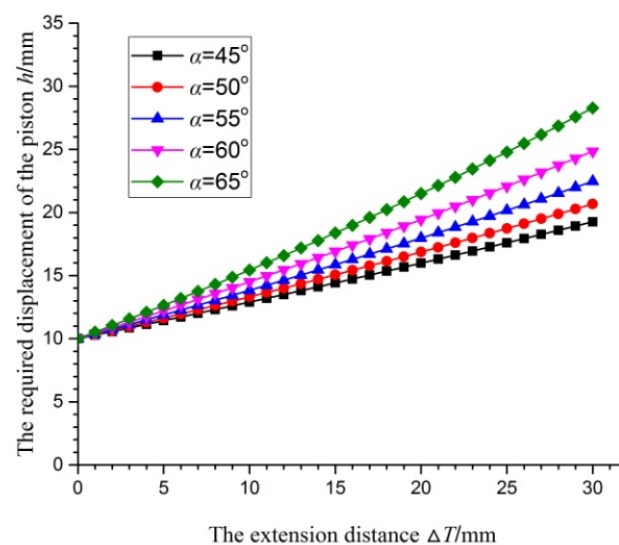


Figure 9. The relationship between the extension distance ΔT and the required displacement of the piston h in different cutter face angles α .

The relationship between the required cutting torque M_{all} and cutter face angle α is shown in Figure 10. The results show that the required cutting torque M_{all} decreases as the angle of the cutter face increases. The above studies show that the choice of cutter face angle α is very important.

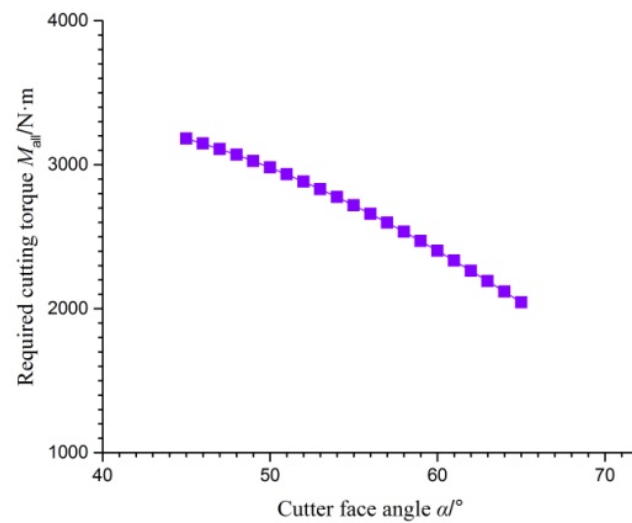


Figure 10. The influence of cutter face angle α on required cutting torque M_{all} .

5.2. The Driving Force of Drilling Fluid F_0

We analyzed the influence of driving force F_0 of the drilling fluid on the wellhead driving torque M while the cutter face angle $\alpha = 55^\circ$, and the results are shown in Figure 11. It shows that the wellhead driving torque M decreases as the angle of the cutter face α increases.

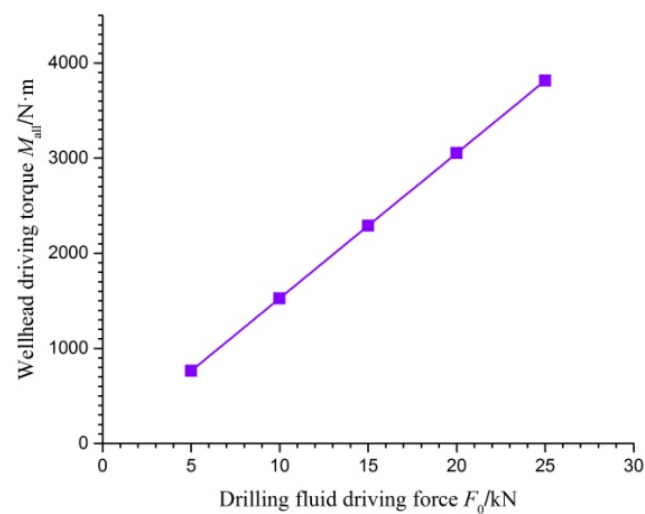


Figure 11. The influence of drilling fluid driving force F_0 on wellhead driving torque M .

5.3. The Cutting Depth L and Revolution of Drill String n

We analyzed the required wellhead driving torque under different drilling revolutions n and different cutting depths L , and the results are shown in Figure 12. It shows that the wellhead driving torque M increases as the depth of cutting increases, and it increases with the increase in drilling revolution n at the same cutting depth. We suggested that when the cutter face angle $\alpha = 55^\circ$, the drilling revolution should not exceed 45 r/min, and the cutting effect is the best while considering the influence factors of cutting torque and drilling revolution.

Since the cutting position of offshore casing cutting is close to the underwater wellhead, the cutting depth is basically the same as the working water depth, and to a certain degree, cutting depth can reflect the influence of water depth on the cutting torque of the wellhead. Therefore, it is reasonable to use cutting depth instead of water depth to analyze the influence of water depth on wellhead torque and cutting torque.

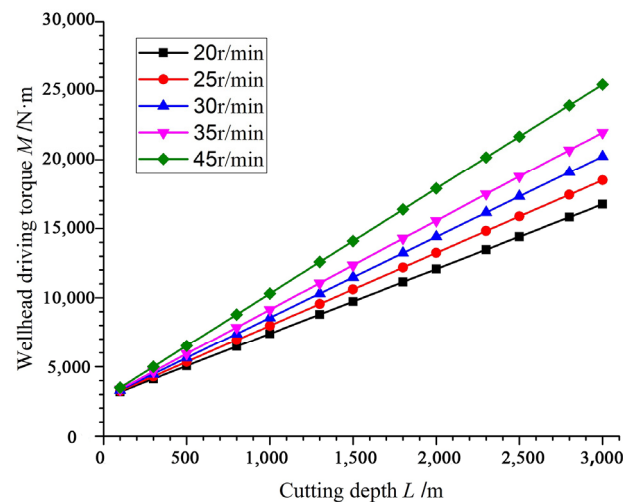


Figure 12. The influence of cutting depth L and drilling revolution n on wellhead driving torque M .

The sudden drop in wellhead driving torque is mainly due to the reduction in the cutting torque during the casing cutting; therefore, the percentage of cutting torque to wellhead torque at different cutting depths is analyzed, and the result is shown in Figure 13. Figure 13 shows that the proportion of cutting torque to wellhead driving decreases as the depth of cutting increases; when the cutting depth exceeds 500 m, the proportion is less than 50%, and the proportion is less than 30% when the cutting depth exceeds 800 m. These results show that it is limiting to use the sudden drop of wellhead driving torque to judge the completion of the casing cutting when the water depth is deep.

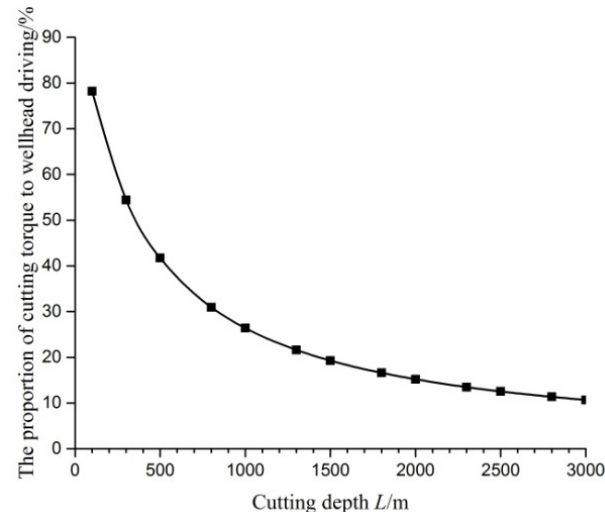


Figure 13. The proportion of cutting torque to wellhead driving with different depths L .

6. Case Study and Discussion

6.1. Field Casing Cutting Operation Condition

Well LH29-2-1 had casing cutting operations during the abandonment operations, which was in the South China Sea. Its cutting depth is nearly 850 m, the outer diameter of the cutting casing is 13-3/8", the pump stroke is 0~70 min⁻¹, the total weight of the drill string is 1040 kN, and the other main parameters of the cutter are the same as in Table 1. The whole cutting process took more than 8 h, and it replaced the original pump due to abnormal pump pressure during casing cutting. The wellhead drilling torque was changed by adjusting the revolution of the pump after changing the pump, and after 2.0 h of constant drilling revolutions (45 r/min), the torque meter showed 7000~14,000 N·m and

there was no sudden torque drop (the torque drops sharply after 10~20 min in shallow water wells). Since it cannot judge whether the cutting has been completed, the drilling string was pulled out and the cutter was checked, and it was found that the wear of three cutters was very serious, especially in the range of the 30 mm near the tip of the cutter, the tip of the cutter was ground basically round, and there are obvious arc scratches on the two pairs of cutters from the tip of the cutter at 120 mm. According to the above indications, the probability of complete casing cutting exceeds 80%, and the cut casing was salvaged by subsequent salvage, as shown in Figure 14.

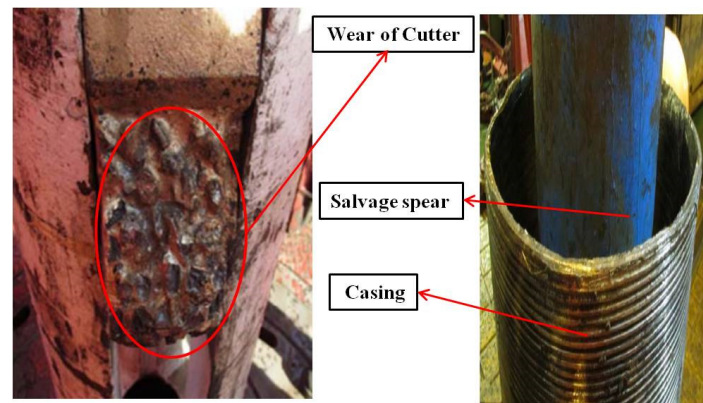


Figure 14. The cutter and casing after removal from the well.

Similar situations occurred in other wells during the casing cutting, and most of the water depths were more than 500 m. The technician in the field believes that this may be due to water depth factors or defects in the design of the device itself. Combining the theoretical analysis with the results of Figures 12 and 13, we believe that the depth of water (cutting depth) should be the main cause of the above situation. The proportion of seawater resistance torque and inertia torque to the wellhead driving torque increases with the increase in the water depth, and this results in a reduction in the ratio of cutting torque to wellhead driving torque (detailed analysis in Section 5.3).

6.2. Torque Comparison at Different Rotational Speeds

For further analysis, we extracted the curve of torque versus time at the middle point of 5 h 20 min of the casing cutting process, as shown in Figure 15.

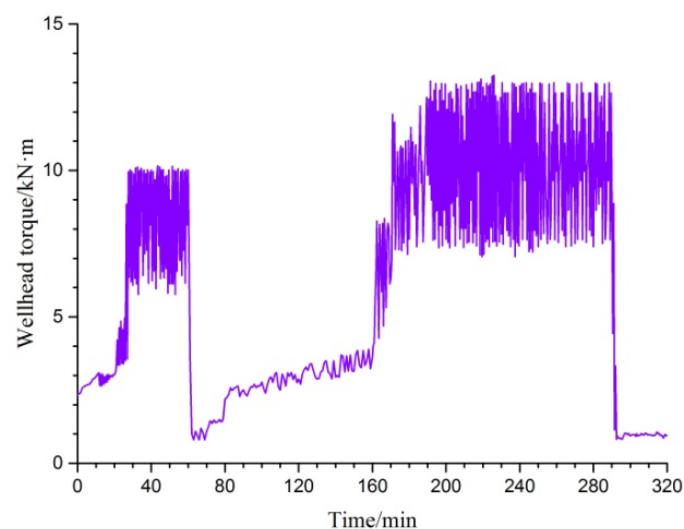


Figure 15. The variation in wellhead drilling torque with time.

The measured wellhead driving torque in the field was compared with the theory at the same pump stroke and drilling revolution as shown in Figure 16. The related data were calculated during the period of the 2# pump since it is consistent with the theoretical parameters and the drilling revolutions of 20 r/min, 25 r/min, 30 r/min, and 45 r/min.

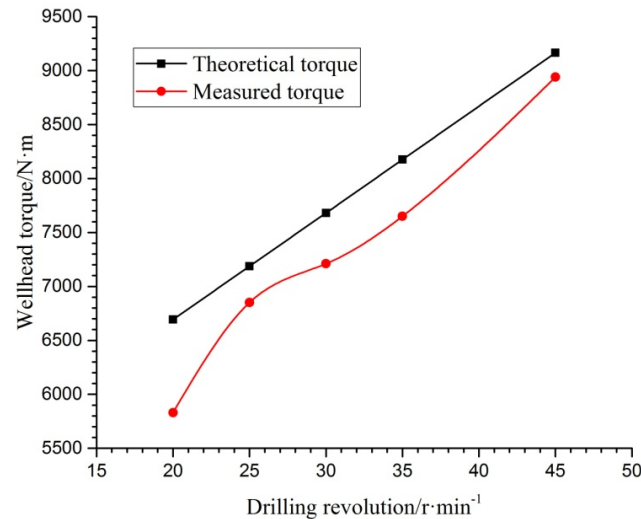


Figure 16. Measured and theoretical values of wellhead driving torque.

According to the results, the theoretical torque obtained at different rotational speeds is basically consistent with the measured torque, and the maximum error between them is 12.89%. The minimum sampling time of the torque measuring instrument is 30 s, and for that measurement, the error is $\pm 10\%$; the changes in measured torque are basically consistent with the theoretical changes, which further explain the correctness of the theoretical model.

7. Conclusions

Based on the structure and working principle of the hydraulic driving mechanical cutting device, the mechanical model of casing cutting is established. We analyzed the relationships between the main structure parameters and the cutting torque, wellhead drive torque, and cutting efficiency, and the specific conclusions are as follows.

- (1) The increase in the extension distance ΔT will lead to the increase in the displacement h required by the piston. When the extension distance increases from 0 to 30 mm, the displacement required by the piston also increases from 10 mm. When the extension distance ΔT is fixed, the displacement h required by the piston will increase with the increase in the cutter face angle α .
- (2) The increase in the tool face angle α will lead to the reduction in the tool cutting torque. When the tool face angle increases from 45° to 65° , the tool cutting torque decreases from about 3200 N·m to about 2000 N·m.
- (3) The cutter face angle α , cutting depth L , and drilling revolution n will affect the driving torque of wellhead M , and the increase in cutter face angle α will reduce the driving torque of wellhead M . The increase in cutting depth L will lead to the increase in wellhead driving torque M . When the cutting depth L is constant, the increase in the drilling revolution n will lead to the increase in the wellhead driving torque M .
- (4) According to Section 5.3, with the increase in cutting depth L , the proportion M_1 / M of cutting torque M_1 to wellhead driving torque M decreases gradually. It cannot judge the completion of the casing cutting according to a sudden drop in wellhead driving torque since the proportion M_1 / M is less than 30% while working in deep water (cutting depth > 800 m).

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