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Research article

Research and development of a self-centering clamping device for deep-water multifunctional pipeline repair machinery

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Abstract

When multifunctional pipeline repair machinery (MPRM) is used in the deep sea area, it is difficult to grip the pipeline and ensure concentricity between the cutter heads and the pipeline during its operation. In view of this, a new system of two-arm holding self-centering pipeline clamping device was proposed. The system is composed of two groups of parallelogram double-rocker mechanism and cranking block mechanism which are symmetrically distributed on the frame. The geometric parameter solutions of the clamping device were analyzed with motion and transmission as the constraints. A mechanical model was established to associate the friction torque of clamping points with the driving force. Clamping device and machinery were designed and manufactured for the Ø304.8–457.2 mm pipelines used in this test. ADAMS simulation experiments were conducted underwater, and the cutting and beveling tests were carried out onshore. The following results are achieved. First, the smaller the pipe diameter, the smaller the transmission angle of the oscillating slider mechanism; the longer the hydraulic cylinder stroke, the greater the transmission angle of the double rocker mechanism. Second, the driving force of the clamping device increases with the increase of the pipe diameter. When the diameter reaches 457.2 mm, the hydraulic cylinder driving force of the clamping device should be greater than 10219 N. Third, the feed rate of the cutters increases suddenly due to the slight shaking of the machinery which occurs at the beginning of the pipe cutting, so it is necessary to adopt a small feed rate. And fourth, onshore experiment results agree well with the theoretical design and simulation results, proving the rationality of the system. The research results in this paper provide technical basis for the research and development of similar engineering prototypes.

Keywords: Deepwater; Submarine pipeline; Multifunctional pipeline repair machinery; Self-centering; Two-arm holding; Clamping device; ADAMS simulation; Experimental study; Bevel

Single-layer welding steel pipelines with minor diameters, large wall thickness and high strengths are extensively used for oil/gas transmission in offshore areas with water depths over 1000 m [1]. Any leakage in such pipelines must be repaired as soon as possible to minimize economic losses and environmental pollution. To repair severely damaged deep-water pipelines, diverless mechanical connection technologies are extensively deployed outside China [2]. These technologies require special equipment and maintenance operations. During the implementation of such operations, operators on the attendant vessel remotely manipulate Remotely Operated Vehicles (ROVs) and underwater facilities. Currently, these technologies are predominantly owned by Statoil, DW RUPE, Subsea 7, BP and ENI/Saipem [3–10]. Prior to pipeline connection, mechanical connectors are required to lower the lifting pipe rack and the supporting pipe rack to lift the pipeline suspended at a predetermined height over the seabed.

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In the course, it is necessary to maintain the pipeline in a horizontal position. Then, it is necessary to lower pipeline maintenance tools to perform pre-processing of concerned pipelines, namely, to cut off and remove the damaged pipeline, remove corrosion-resistant coating (Fusion Bond Epoxy, FBE) and weld seams before the fabrication of bevels on both ends of the pipeline. To perform such operations, close coordination of these three tools for pipeline cutting, fabrication of bevels and removal of corrosion-resistant coating (weld seam) is required. Implementation of such operations may involve multiple lifting operations for relevant tools. Moreover, manipulation of such tools by using ROVs in deep water environments may face difficulties in secondary positioning. These difficulties may eventually reduce operation efficiency and increase maintenance costs [11]. Currently, China has facilities and technologies available to repair failed pipelines in shallow waters only. Harbin Engineering University has conducted relevant researches for tools and technologies related to the maintenance of deep water pipelines. With the deep-sea Liwan-3-1 Gasfield in the South China Sea put into production, development of deep water multifunctional pipeline repair machinery became more important.

This paper reviewed technologies related to clamping devices in tools for deep-water pipeline operations. With consideration to the specific features of deep-water multifunctional pipeline repair machinery, structural design of clamping devices has been accomplished. ADAMS simulation experiments were conducted to determine the reliability of such clamping devices. In addition, cutting and beveling tests were carried out by using the prototype.

1. Technologies related to the clamping devices for deep water pipelines

Due to the stationary submarine pipelines and the specific features in deep-water environment, it is impossible to secure pipeline operation tools on the seabed. Internationally, all deep-water pipeline operation tools deploy “two-arm holding” or “one-arm holding” clamping devices to secure relevant devices on the pipeline prior to relevant operations [12,13].

Fig. 1 shows a typical structure of a pipeline clamping device with “two-arm holding”. With symmetric structure, the device is composed of supporting rack, hydraulic cylinder and clamping claw. The supporting rack may have “V” or quarter-circular configurations. By using the device, it is possible to clamp the pipeline from the top. In addition, the device may provide relatively high clamping forces to secure pipelines with certain diameters. However, the device may not be used to rotate the operation tools to align these tools with the pipeline as required for circumferential operations on pipelines with different diameters. Consequently, the pipeline clamping device with “two-arm holding” can be used predominantly for operations without requirements for alignment, such as cutting operations involving diamond wire saw [14] or guillotine pipe saw [15].

Fig. 2 shows a typical structure of a pipeline clamping device with “one-arm holding”. Composed of rack, hydraulic cylinder, guide rail and clamping claw, the device has compact structure with rack and clamping claw in arc configuration. The device can be used to secure the pipelines with certain diameters sideway. When tightened, the rack may in contact with the pipeline in oval arc to facilitate alignment operations. With only one driving cylinder, loads of deep-water hydraulic system can be reduced effectively. Moreover, resulting clamping forces are also relatively small. These devices are predominantly deployed on tools to remove the corrosion-resistant coating of pipelines through milling or abrasion.

2. Working principles and prototype of deep-water multifunctional pipeline repair machinery

Based on investigation on deep-water pipeline maintenance and repair experiences in other countries, the concept of deep-water multifunctional pipeline repair machinery was proposed. In addition, overall structure of the machinery was clarified and the prototype was designed. See Fig. 3 for 3D structure model of the prototype. Generally, the machinery is composed of three packages of power heads, rotary cutting heads, racks, clamping devices, hydraulic valve cabins, underwater control systems, ROV connecting devices, buoyancy materials and other components.

By using two packages of clamping devices, the machinery can secure itself on the pipeline to be processed. The cutting

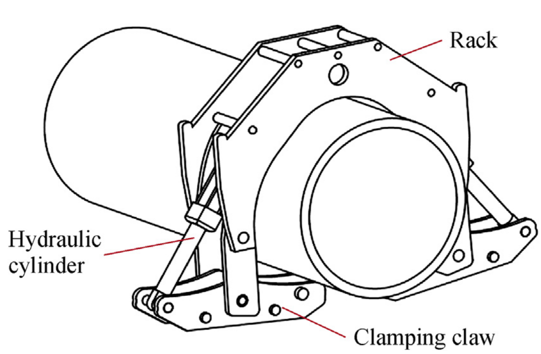


Fig. 1. A pipeline clamping device with “two-arm holding”.

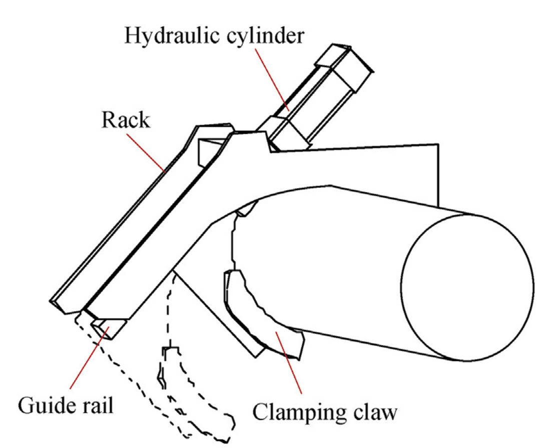


Fig. 2. A pipeline clamping device with “one-arm holding”.

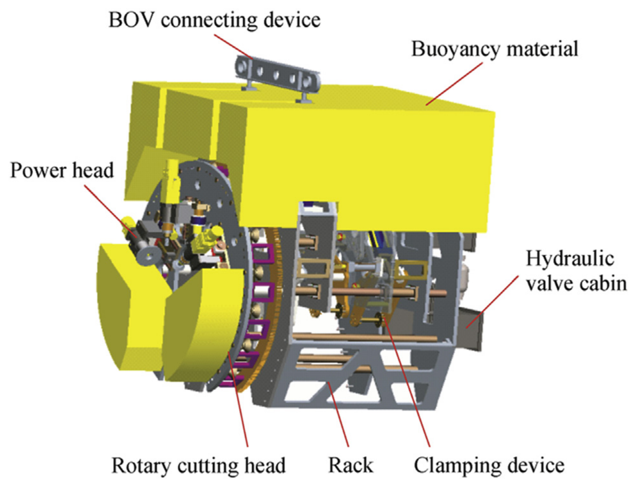


Fig. 3. Deep-water multifunctional pipeline repair machinery.

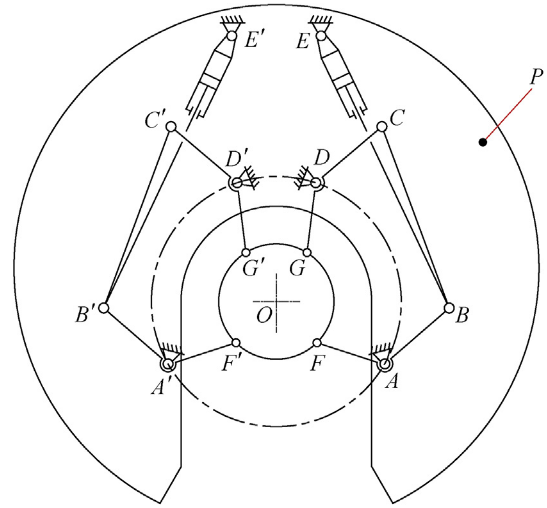


Fig. 4. Operation principles of the clamping device.

system composed of a cutting power head and a rotary cutting head can be used for pre-processing of the pipeline. Since the cutting devices are required to rotate around the pipeline, both the rotary cutting head and the rack have a "C" configuration. The hydraulic valve cabin contains a hydraulic valve with the cabin itself filled with oil and connected with the compensator [16] to ensure automatic compensation to pressures of seawater. ROV can be connected through designated connecting devices to carry the machinery to the target pipeline.

3. Design of the clamping device

3.1. Technical requirements

To cope with working environments and objectives of deep-water multifunctional pipeline repair machinery, the clamping device should meet the following technical requirements. First, it can tightly secure the pipeline in place with no displacement allowed between the device and the pipeline during operation. Second, it should be suitable for pipelines with diameters in certain extent (304.8–457.2 mm). And third, rotation center of the rotary cutting head should align with pipeline axis during operations involving pipelines of different diameters by using the device, since O-ring in flange of the connector may present higher requirements for ellipticity and concentricity of pipeline's bevel, when pipelines are repaired by using mechanical connection techniques.

3.2. Design principles

For meeting the above requirements, the design of two-arm holding self-centering clamping device was proposed. See Fig. 4 for working principles of the device. The device is composed of 6 rocks in two groups distributed symmetrically on both sides of Rack *P*. Each group contains parallelogram double-rocker mechanism and cranking block connected in series. As to the geometric parameters of the device, *ABCD* ($A'B'C'D'$) is the plane double-rocker mechanism with *BE* ($B'E'$) as the driving hydraulic cylinders and *AB* ($A'B'$) as the active rockers, and *BC* ($B'C'$) are connecting rods and *CD* ($C'D'$) are passive rockers. The double-rocker mechanism has parallelogram configuration with identical extension of different rockers ($l_{AF} = l_{DG}$, $l_{A'F'} = l_{D'G'}$ and *F*, *G*, F', G' are holding points). Centers of anchoring hinges, *A*, *D*, A' and D' distributed on the concentric circle with the center of the device, *O*, as the circle center symmetrically on both sides of the rack. Specific features of the device can be summarized as follows: the device may enable clamping of the pipeline from the top section during under-water operations. Whenever hydraulic cylinders are deployed to hold the pipeline in place, 4 holding points on both left and right double-rocker mechanisms may simultaneously move on the concentric circle around the center point, *O*, of the clamping device. In this way, it is possible to ensure proper alignment between the rotation center of the cutting head and the pipeline axis during holding pipelines with designated diameters in place.

3.3. Geometric parameters

With the clamping device on the right side as the research objective, Fig. 5 shows the tightening of the pipeline by the clamping device. Origin point, *O*, of the coordinate system $O - xy$ is the rotation center of the rack (concentric with the pipeline); *R* is the radius of the anchoring hinge circle; *r* is the pipeline radius; θ is the included angle between *OF* and *OA*; coordinates of Point *A* are (*R*, 0), φ is the included angle between *AB* and the *x*-axis; β is the included angle between *OD* and *OA*; γ is the included angle between *EB* and *AB*; α_4 is the exterior angle of *OF* and *AF*.

3.3.1. Determination of the rocker length

For obtaining desirable clamping performances, Point *G* of the clamping device should be maintained within the first quadrant, whereas Point *F* should be maintained in the fourth quadrant, during the clamping of pipelines with various diameters. Suppose the pipeline with minimum diameter is clamped, $\theta = 0°$, l_{AF} reaches the minimum length:

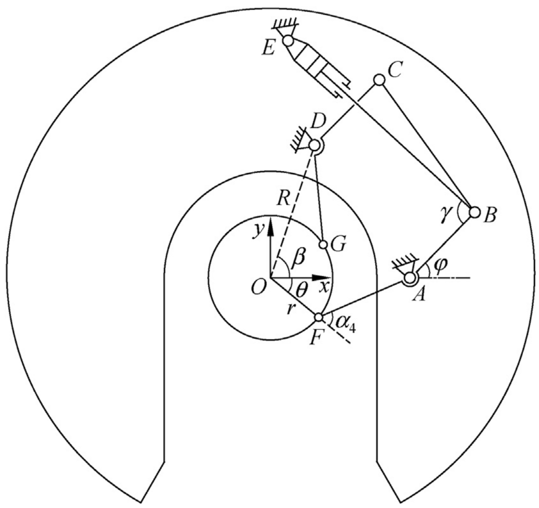


Fig. 5. Clamping of the pipeline.

$$l_{AF} = R - r_{\min} \tag{1}$$

With consideration to geometric constrained conditions of the device,

$$l_{AB} = 1.1\, l_{AF} \tag{2}$$

3.3.2. Determination of l_{AD} and β

During the initial stage of installation, the clamping device may sit on the back of the pipeline with the coordinate system, $O - xy$, of the clamping device aligned with the y-axis in the coordinate system, $O' - x'y'$, of the pipeline, as shown in Fig. 6. At this time, the clamping device is not coaxial with the pipeline. When the hydraulic cylinders are started, active rocker and passive rocker of the clamping device may move simultaneously. Holding point, G, of the passive rocker may contact the pipeline first before upward traveling circumferentially along the pipeline to raise the device gently. When the holding point, F, of the active rocker gets in touch with the pipeline, piston rods in the hydraulic cylinder may no longer extend. At this time, the clamping device may be securely fastened on the pipeline. To lift up the system, the clamping device is required to have the holding point, G, in the first quadrant of the coordinate system of pipelines with any given diameter. Accordingly, the coordinates of anchoring hinge point D should conform to the following equation sets:

$$\begin{cases} (x_D - x_G)^2 + (y_D - y_G)^2 = l_{DG}^2 \\ x_D^2 + y_D^2 = R^2 \end{cases} \tag{3}$$

Geometric constrained conditions: $x_D > 100$, $y_D > R_o - r$, $\alpha_0 > 0°$.

In which, $x_G = r\cos\alpha_0$; $y_G = r\sin\alpha_0 + R_o - r$; (x_D, y_D) are coordinates of Point D in the coordinate system of the device; (x_G, y_G) are coordinates of Point G in the coordinate system of the device at the first contact with the pipeline; R_o is the radius of the inner arc of the rack; α_0 is the included angle between $O'G$ and x' axis. Analysis results show that the minimum pipeline diameter in holding can satisfy the requirements related to the coordinates of Point D. Accordingly, pipelines with other diameters may also satisfy the above-mentioned requirements. Consequently, coordinates of Point D, l_{AD} and β can be determined as long as the suitable α_0 has been taken.

3.3.3. Coordinates of Point E

To maintain steady movements of the clamping device, transmission angle γ and $\angle BCD$ of the cranking block and the double-rocker mechanism at any given time in movements of the clamping device are required to be higher than 40°. It can be seen in Fig. 5 that coordinates of Point E should conform to the following equation set.

$$\begin{cases} \cos\gamma = \dfrac{BA \cdot BE}{|BA| \cdot |BE|} \\ \cos\angle BCD = \dfrac{CB \cdot CD}{|CB| \cdot |CD|} \\ |BA| = l_{AB} \\ |BE| = l_{EB} \end{cases} \tag{4}$$

Geometric constrained conditions: $x_E \in [200, 400]$, $y_E \in [400, 600]$, $l_{EB} \in [550, 750]$.

According to the features in the movements of the clamping device, the minimum transmission angle, γ, of the cranking block can be observed during the clamping of the pipeline with the minimum diameter. At this time, longest l_{BE} can also be observed. With (x_E, y_E), l_{EB} deployed in the above equation set, (x_E, y_E), (x_B, y_B) and φ can be determined as long as the transmission angle, γ and $\angle BCD$ conform to the relevant constrained conditions.

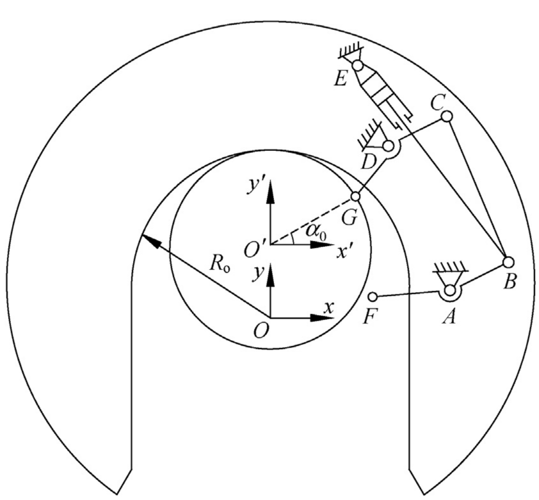


Fig. 6. The clamping device at the initial stage of installation.

3.4. Design examples

Given $R = 350$ mm, $r = 152.4$ mm, $\alpha_0 = 10°$, $l_{EB} = 750$ mm and $R_0 = 254$ mm, actual dimensions of the clamping device can be determined as shown in Table 1. Table

Table 1
Calculation parameters of the clamping device.

Parameters	Values
l_{AF}/mm	200
l_{AB}/mm	220
l_{AD}/mm	396.11
x_E/mm	200
y_E/mm	600
l_{EB}/mm	750
α_0/(°)	10
$\angle BAF$/(°)	200.72
$\angle CDG$/(°)	269.65
$\angle BCD$/(°)	139.35
β/(°)	68.93
γ/(°)	46.2

Table 2
Actual parameters of the clamping device.

Parameters	Values
l_{AF}/mm	200
l_{AB}/mm	220
l_{AD}/mm	396
x_E/mm	200
y_E/mm	600
l_{EB}/mm	747.99
α_0/(°)	9.53
$\angle BAF$/(°)	200
$\angle CDG$/(°)	270
$\angle BCD$/(°)	138.61
β/(°)	68.93
γ/(°)	46.78

2 shows the actual dimensional parameters of the clamping device after rounding. In the table, length is expressed in mm and angle is in degrees.

See Table 3 for correlation between transmission angle and the rocker length, l_{EB}, during the clamping of pipelines with different diameters by the clamping device.

It can be seen in Table 3 that the hydraulic cylinder has traveling distance of 172.64 mm. When clamping pipelines with diameters at 304.8−457.2 mm, transmission angle γ and $\angle BCD$ of the devices are all higher than 40°. Accordingly, it can be seen that the device has outstanding transmission stability. See Fig. 7 for 3D model of the clamping device and see Fig. 8 for the actual prototype.

Table 3
Correlation among pipeline diameter, transmission angle and rocker length (l_{EB}).

Parameters	Values				
D/mm	304.8	355.6	406.4	457.2	558.8
l_{EB}/mm	747.99	702.33	670.76	641.73	575.35
$\angle BCD$/(°)	138.61	123.66	114.42	106.39	88.88
γ/(°)	46.78	59.00	66.89	74.02	90.70
α_4/(°)	13.51	44.31	59.54	70.69	87.72

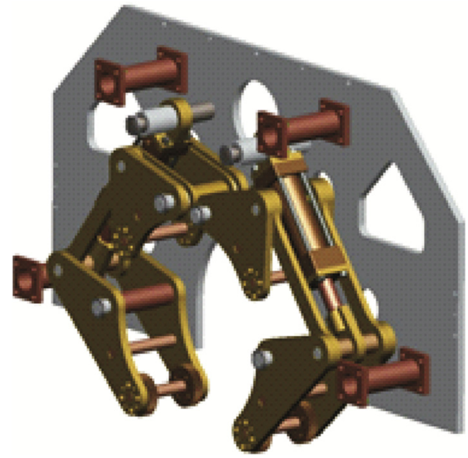


Fig. 7. 3D model of the clamping device.

Fig. 8. A clamping device.

4. Mechanical analysis for underwater operations of the clamping device

During underwater operations, the device may tend to rotate around the pipeline axis due to overturning torque (cutting resistance, gravity eccentric torque and current torque). For maintaining steady operations of the device, all holding points in front of and at the back of the clamping device are required to balance the combined friction torque and overturning torque along the pipeline axis.

Since frontal and back clamping devices have identical structures, the frontal clamping device should be taken as the objective for the concerned research. If the axis of left and right hydraulic cylinders in the clamping device distributed in Plane p, the coordinate system can be established with the crossing point between pipeline axis and Plane p as the original point of the coordinate system, and with the vertical upward direction as the y-axis direction and with the horizontal rightward direction as the direction of x-axis. See Fig. 9 for forces on Plane xoy during the tightening of the pipeline by the clamping device under a critical equilibrium state.

In Fig. 9, N_i is the positive pressure on the holding point of the clamping device; f_i is the friction on the holding point; F_1 and F_2 are forces on the connecting rod; F_{ye} is the hydraulic cylinder driving force; M is the overturning torque.

4.1. Model for the correlation between friction torque and driving force

Once the pipeline has been secured by the clamping device, torques on various anchoring hinges can be determined by using the following torque equilibrium equations.

$$\begin{cases} f_1 l_{DG} \cos\alpha_1 + F_1' l_{CD} \sin\alpha_2 = N_1 l_{DG} \sin\alpha_1 \\ N_4 l_{AF} \sin\alpha_4 - f_4 l_{AF} \cos\alpha_4 + F_1 l_{AB} \sin\alpha_3 = F_{ye} l_{AB} \sin\gamma \\ N_2 l_{D'G'} \sin\alpha_1' + f_2 l_{D'G'} \cos\alpha_1' = F_2' l_{C'D'} \sin\alpha_2' \\ N_3 l_{A'F'} \sin\alpha_4' + f_3 l_{A'F'} \cos\alpha_4' + F_2' l_{A'B'} \sin\alpha_3' = F_{ye} l_{A'B'} \sin\gamma' \end{cases} \tag{5}$$

According to the features of the device, $\alpha_i = \alpha'_i$, $\alpha_1 = \alpha_4$, $\alpha_2 + \alpha_3 = 180°$. Since devices in the front and at the back are identical, Eq. (5) can be used to derive the following equation:

$$T_f = \sum_{i=1}^{8} \mu N_i r = 2\mu \frac{l_{AB}}{l_{AF}} F_{ye} \sin\gamma \left(\frac{2\sin\alpha_4}{\sin^2\alpha_4 - \mu^2 \cos^2\alpha_4} \right) r \tag{6}$$

In which, T_f is the joint friction torque imposed on pipeline axis by the holding points; μ is the sliding friction coefficient.

4.2. Steady operation conditions

Mathematical model for steady operation of the device can be expressed as follows:

$$T_f \geq T_T + T_G + T_W \tag{7}$$

In which, T_T is the resistant torque for cutting operations; T_G is the eccentric torque; T_W is the current torque.

The device may experience maximum resistant torque for cutting and milling operations during operations involving pipelines with diameter of 457.2 mm. By using the empirical formula for such operations, T_T can be determined to be 1030.4 Nm. T_G of the device in water is approximately 0.9 Nm with T_W about 18.3 Nm. Accordingly, $T_f \geq 1049.6$ Nm is required to maintain the device in a steady operation state.

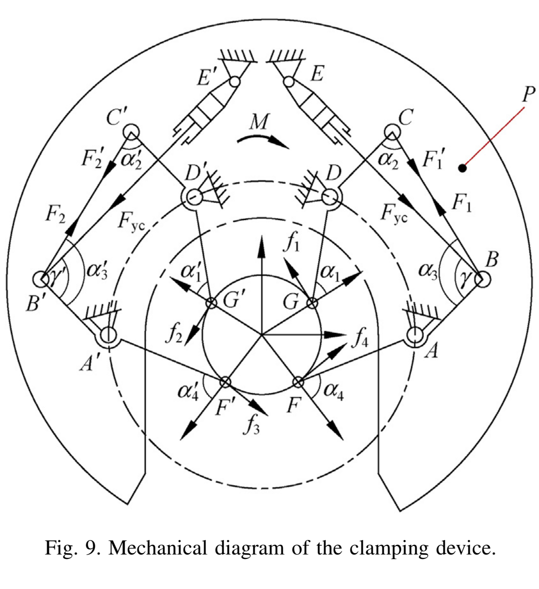


Fig. 9. Mechanical diagram of the clamping device.

4.3. Determination of the driving force of the hydraulic cylinder

With $T_f = 1050$ Nm and $\mu = 0.15$, the driving force of the hydraulic cylinder can be determined by using Eq. (6) and Table 3, as is shown in Fig. 10. It can be seen from Fig. 10 that the maximum driving force of the hydraulic cylinder is required during the steady operations of the device on pipelines with diameter of 457.2 mm. At this time, minimum driving force of the hydraulic cylinder is expected to be 10219 N.

5. Simulation of underwater operations by the clamping device

By using ADAMS, simulation can be performed for underwater operations of the designed clamping device. See Fig. 11 for the simulation model of the clamping device. Since assistants of ROV are required for operations of the clamping device, torques of currents can be ignored during simulation. During the simulation process, step functions can be deployed to input driving forces of the hydraulic cylinder: step (time, 0, 0, 15, 15000); overturning torques: step (time, 0, 0, 22, 0) + step (time, 22, 0, 25, 1050). Then, it is necessary to determine the coordinates of the rack center, *O*, shown in Fig. 6 in the coordinate system of the pipeline. The following situations can be seen from Fig. 12. First, coordinates of Point *O* under steady state of

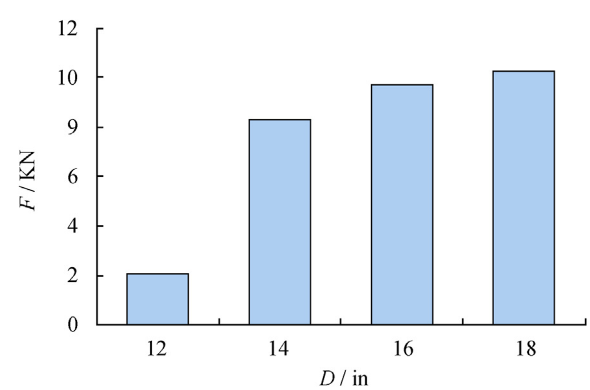


Fig. 10. Correlation between the driving force of the hydraulic cylinder (F) and pipeline diameter (D). Note: 1 in = 25.4 mm, the same below.

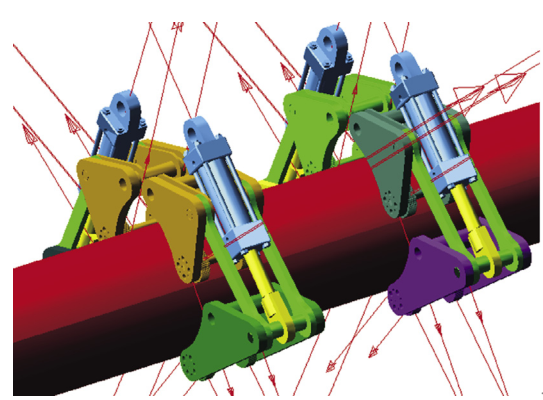


Fig. 11. A simulation model of the clamping device.

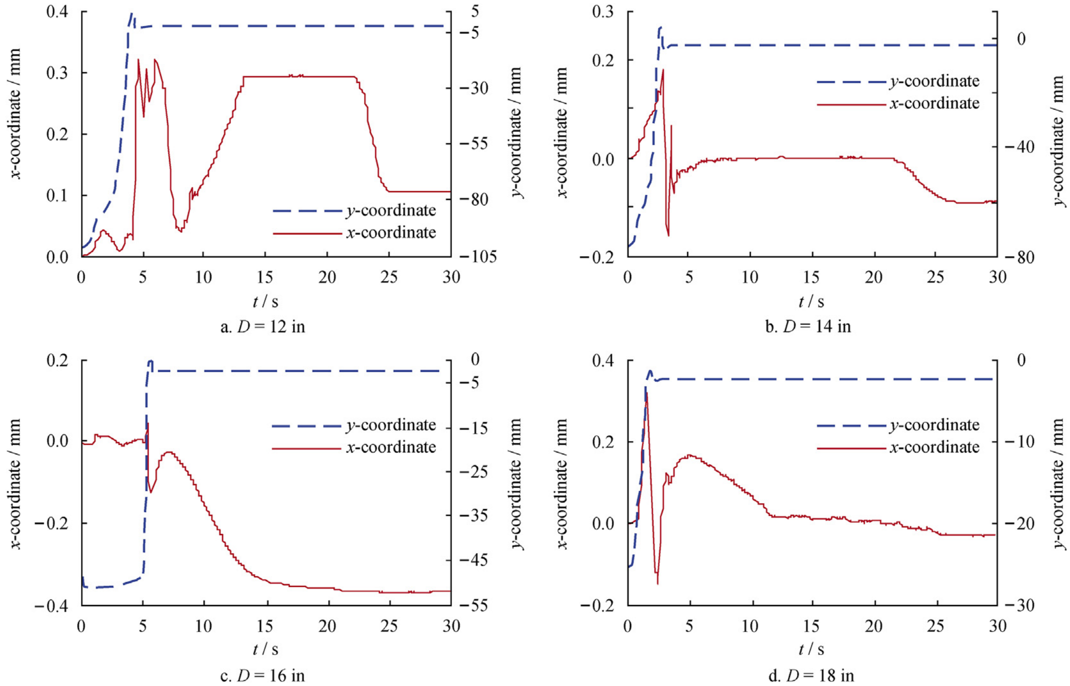


Fig. 12. Coordinates of Point O of the clamping device rack.

the clamping device are (0.19, −1.89), (−0.01, −2.39), (−0.343, −2.37) and (−0.001, −2.31), respectively. Once the overturning torques have been deployed, clamping device may regain steady state after short adjustments with coordinates of Point O at (0.11, −1.9), (−0.09, −2.4), (−0.37, −2.35) and (−0.03, −2.32), respectively. It can be seen that the clamping device has excellent self-centering capabilities. Second, deployment of overturning torques may lead to drifting with maximum volume (0.08, 0.02) of the cutting devices. Under such circumstance, feed of the device may increase rapidly, and consequently generate negative impacts on the cutting devices. Accordingly, such conditions should be considered in the selection of cutting tools and cutting parameters.

6. Tests of maintenance tools for on-land cutting and generation of external bevel

Tests of maintenance tools for on-land cutting and generation of external bevel were conducted on single-layer submarine pipeline with diameter of 457.2 mm to determine the clamping and centering capabilities of the clamping device. See Fig. 13 for more details related to the testing system of such tools. Cutting devices deployed in such tests are compound tools with drilling and milling functions with diameter of 25 mm.

On-land tests of the cutting and generation of the external bevel by using the maintenance tools can be performed in the following procedures.

1) Make all necessary preparations, such as positioning of the pipe, deployment of relevant tools, and connection of the hydraulic system.

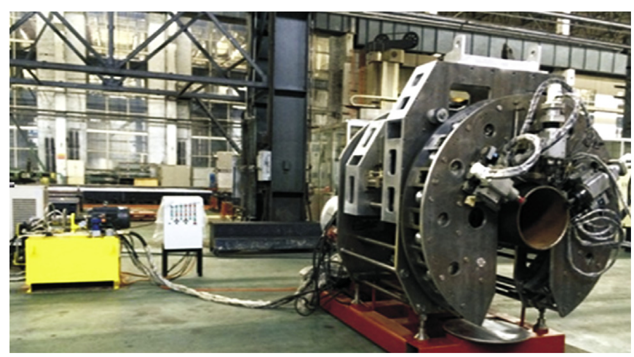
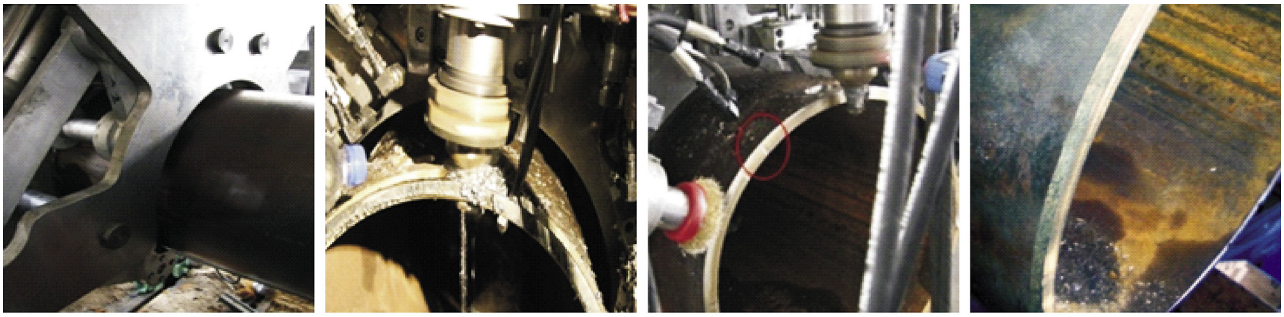


Fig. 13. On-land testing system for the multifunctional pipeline repair machinery.

2) Start the control system and hydraulic pump station to maintain system pressure at 10 MPa.
3) Hydraulic cylinders in front and back clamping devices may be triggered simultaneously to drive the device to hold the pipe tight.
4) Cut off radial feeding of the power head to penetrate the pipe.
5) Start circumferential feeding of the rotary cutting head with the end mill milling the pipe circumferentially.
6) Start circumferential feeding of the rotary cutting head to deploy the chamfer cutter to generate external bevel.
7) Suspend circumferential feeding with power head and clamping claw restored to their original positions, respectively.

See Fig. 14 for major operation procedures. It can be seen in Fig. 14b that the clamping device can securely fasten the maintenance devices under 10 MPa. It can be seen in Fig. 14d that the clamping device has superior centering capabilities.



a. Clamping the pipe b. Cut off the pipe c. Formation of the external bevel d. A partial enlarged view

Fig. 14. Tests for the cutting and formation of the external bevel by using the device.

7. Conclusions

With consideration to the specific features of deep-water multifunctional pipeline repair machinery, analysis was performed for clamping devices deployed for operations involving deep water pipelines. In addition, the design of clamping devices with "two-arm holding" for self-centering pipelines was proposed accordingly. Clamping device and maintenance tools were designed and fabricated for pipelines with diameters at 304.8–457.2 mm. Moreover, ADMAS simulation for underwater operations and tests for the cutting and formation of bevel were performed on land to reach following conclusions:

1) The smaller the pipe diameter, the smaller the transmission angle of the oscillating slider mechanism; the longer the hydraulic cylinder stroke, the greater the transmission angle of the double rocker mechanism.
2) The driving force of the clamping device increases with the increase of the pipe diameter. When the diameter reaches 457.2 mm, the hydraulic cylinder driving force of the clamping device should be greater than 10219 N.
3) The feed rate of the cutters increases suddenly due to the slight shaking of the machinery which occurs at the beginning of pipe cutting, so it is necessary to adopt a small feed rate.
4) Onshore experimental results agree well with the theoretical design and simulation results, which prove the rationality of the system. The research results in this paper provide technical basis for the research and development of similar engineering prototypes.

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