Study on Anti-overturning self-locking device of CRDM for Offshore Nuclear Power Platform

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Abstract. The offshore floating nuclear power plant is an organic combination of offshore ship platform engineering and nuclear power engineering. Its operation is affected and restricted by marine environmental conditions. Under extreme sea conditions, serious nuclear safety accidents can be caused by the capsizing of ship platforms. The passive anti-overturning self-locking device proposed in this paper can lock the drive rod connected to the control rod when the platform overturns, preventing the control rod from exiting the core and ensure the safety of the reactor core. The test results show that the control rod self-locking of the control rod driving mechanism can be realized after the tilt of the ship platform exceeds 90 degrees. It is an important means to ensure nuclear safety and efficiency for offshore floating nuclear power plant under the overturning condition of the ship platform.

Keywords: Floating nuclear power plant; CRDM; Passive; Overturn-preventing; Self-locking device.

1. Introduction
Floating nuclear power station is an organic combination of offshore ship platform engineering and nuclear power engineering, and its operation is affected and restricted by marine environmental conditions[1-2]. Control rod drive mechanism (CRDM) is the actuator of nuclear reactor control system and nuclear safety protection system of floating nuclear power station. Under the marine environment conditions such as tilt, swing and impact of ship platform, CRDM can lift, insert and maintain control rod assembly according to instructions, thus realizing the functions of reactor startup, power regulation, power maintenance and normal shutdown [3].

In extreme sea conditions, the tilt of the platform can trigger the reactor shutdown signal, at this time, the control rod can quickly drop into the core and insert into the core to realize safe shutdown; in the process of platform overturning, when the tilt angle exceeds 90 degrees, the control rod will slowly exit the core under the action of its own gravity, causing the reactor to be critical, leading to serious nuclear safety accidents.

A passive anti-overturning self-locking device is proposed in this paper. It is a kind of mechanical device which can lock the driving rod connected with the control rod to keep the control rod from withdrawing from the core after the platform overturning, maintain the sub critical state of the reactor and ensure the safety of the reactor [4]. It is an important and effective means to ensure the nuclear
safety of the offshore floating nuclear power station under the condition of the ship platform overturning.

2. Main structure of passive anti-overturning self-locking device

The assembly diagram of passive anti-overturning self-locking device for control rod drive mechanism of floating nuclear power station is shown in Figure 1.

![Assembly diagram of overturn-preventing and self-locking device of CRDM](image)

Figure 1. Assembly diagram of overturn-preventing and self-locking device of CRDM

The passive anti overturning self-locking device is installed inside the pressure housing and is located near the top of the driving rod. In the process of platform overturning, the ball slider in the self-locking device moves ahead of the drive rod of the control rod drive mechanism to lock the drive rod so that the control rod connected with it does not exit the core.

![Structural drawing and object of anti-overturning self-locking device](image)

Figure 2. Structural drawing and object of anti-overturning self-locking device

The structure of anti-overturning self-locking device is shown in the left figure of Figure 2. It is mainly composed of gland, slide seat, ball slide and base. There are two C-type guide grooves on both sides of the ball slider, each of which has four small balls and is covered with a press plate to prevent the ball from falling off; six ball sliders are evenly arranged on the groove seat along the circumference so that the ball slider can only slide along the guide rail of the groove seat; the sliding groove seat is installed in the base together with six ball sliders, and the pressure cover is installed at the top to form an integral, anti-overturning. The parts of anti-overturning self-locking device are shown in Fig. 3
During the normal operation of the self-locking device, its ball slider is hidden in the chute seat, which does not affect the functions of control rod lifting, holding and inserting down; in the process of platform overturning, each slide rail of the self-locking device has an included angle of 30° with the driving rod to ensure that at least one slider moves ahead of the driving rod to block the drive rod to realize self-locking.

3. Theoretical analysis of anti-overturning self-locking device

When the platform of offshore floating nuclear power station is overturned, the reactor shutdown is triggered, and the control rod is inserted into the core rapidly; when the platform continues to overturn, the slider can slide down before the drive rod to block the drive rod, which indicates that the control rod self-locking can be realized.

3.1. Motion analysis of self-locking device.

In the anti-overturning self-locking device, the angle α between the slide guide direction and the driving rod is designed to be 30°; when the ship platform is inclined, the angle between the deck surface and the horizontal plane is β (when the ship platform is in the horizontal position, β is 0), and the control rod drive mechanism is completely vertical to the deck surface, so the included angle between the axis of the driving rod and the horizontal plane in the vertical direction is also β. During the capsizing process of the ship platform, with the increase of the overturning angle β, the ball slider and the driving rod begin to slide successively, and the relationship diagram is shown in Fig. 4. In order to simplify the calculation, the influence of water resistance is not considered when the ball slider and the driving rod start to slide, only the influence of material friction resistance is considered.

3.1.1. Overturning angle β value of sliding ball slide. With the increase of the ship platform overturning β angle, there is a positive angle γ between the slide guide rail and the horizontal plane, and the sliding block starts to slide under the action of gravity to overcome the friction resistance of the guide rail. According to figure 4 (a), the overturning angle β is: β=90°-(α-γ);
When the sliding block starts to slide, the component force generated by gravity is equal to the frictional resistance without considering the influence of water resistance.

\[ mg \sin \gamma = \mu mg \], To simplify the formula:

\[ \gamma = \arcsin \mu \]  

(1)

Where: \( m \) is the mass of sliding block;
Friction resistance of materials;
According to the mechanical design manual, the static friction coefficient between metals is 0.15-0.3, which can be obtained by substituting it into the above formula \( 1: \gamma = 8.6^\circ \sim 17.5^\circ \);
According to \( \beta = 90^\circ - (\alpha - \gamma) \), it can be calculated that the platform overturning \( \beta \) angle is 68.6\(^\circ\) to 77.5\(^\circ\), that is, when the platform overturns between 68.6\(^\circ\) and 77.5\(^\circ\), the ball slider starts to slide out, and the angle between the driving rod and the horizontal plane is less than 90\(^\circ\) and will not slide out.

3.1.2. Overturning angle \( \beta \) value of driving rod sliding. The angle between the driving rod and the vertical plane and the overturning angle \( \beta \) are equal. If the driving rod starts to slide down against its own gravity, the \( \beta \) value must be greater than 90\(^\circ\) and the angle between the driving rod and the horizontal plane is \( \theta \), then the value of \( \theta \) is: \( \theta = \beta - 90^\circ \). When water resistance is not considered, the sliding of driving rod is only affected by friction resistance. According to Fig. 4 (b), overturning \( \beta \) can be obtained.

\[ \beta = 90 + \arcsin \mu \]  

(2)

Substituting the value of 0.15-0.3 into formula 2, it can be concluded that \( \beta = 98.6^\circ \) to 107.5\(^\circ\) and the angle between the ball slider guide and the vertical line is 128.6\(^\circ\) to 137.5\(^\circ\) and the slide has already slipped out.

3.2. Self-locking analysis of self-locking device
According to Section 2.1, when the platform is overturned to 68.6\(^\circ\) to 77.5\(^\circ\) the sliding block starts to slide but the driving rod does not; when the platform is overturned to 98.6\(^\circ\) to 107.5\(^\circ\) the driving rod starts to slide. Taking the most extreme case as an example, suppose that the time of platform overturning from 77.5\(^\circ\) to 98.6\(^\circ\) is \( t_0 \). As long as the sliding time \( t < T_0 \), the slider will slide ahead of the driving rod and lock the driving rod successfully.

3.2.1. Analysis of sliding time of slide block. According to the design size of the self-locking device slider, the sliding distance \( S = 14\text{mm} \) from the top of the slide rail to the bottom; with the increase of the angle between the sliding block and the horizontal plane, the sliding block starts to slide against its own gravity, and the sliding acceleration: \( a = g \sin \gamma - \mu \cos \gamma \); according to the relationship between displacement and acceleration \( s = \frac{1}{2}at^2 \), the sliding time formula of the sliding block to the bottom can be obtained as follows:

\[ t = \sqrt\frac{2s}{a} = \sqrt\frac{2s}{g \sin \gamma - \mu \cos \gamma} \]  

(3)

When \( \gamma = 8.6^\circ \) to 17.5\(^\circ\) is substituted into formula 3, the sliding time of sliding block can be calculated: \( T_{\text{max}} = 0.333s; T_{\text{min}} = 0.0632s \); therefore, when the platform overturns from 77.5\(^\circ\) to 98.6\(^\circ\) for more than 0.333s, the self-locking device must be able to lock the driving rod successfully.
3.2.2. Overturning time of ship platform. According to publicly available data, there have been major ship capsizing and sinking events at sea. The time from the beginning of the capsizing to the turning over of the hull at 90 degrees till the full capsizing has exceeded 10 minutes; in some cases, from the turning over of 45 degrees to the full capsizing has lasted for several hours [5-7]. In the latest large-scale marine capsizing accident, for example, the rollover accident of the South Korean Shiyou passenger ship is 145.6m long, 22.00m wide and 6.26m draught with a total tonnage of 3794 tons. On April 16, 2014, at 7:55, the hull was severely impacted and tilted; at 9:31, the ship rolled over; at 11, the ship sank completely; and the Shiyou rolled over from tilt to side, taking 1 hour and 36 minutes.

As a large ship, the offshore nuclear power platform has considered the ship stability in design. According to the above accident analysis, the overturning process of the platform is much more than 10 minutes.

3.2.3. Theoretical analysis results. According to the theoretical calculation results, the ball slider of the self-locking device can slide out when the platform is overturned between 68.6 degrees and 77.5 degrees, and the driving rod can slide out between 98.6 degrees and 107.5 degrees; in the most extreme case, if the platform is overturned from 77.5 degrees to 98.6 degrees for more than 0.333s, the self-locking device can lock the driving rod; and according to the existing ship design characteristics and the ship overturning that has occurred. In case of overturning accident, the overturning process of ship platform is much longer than this time, so the self-locking device can successfully realize the self-locking function of control rod.

4. Design of test stand for anti-overturning self-locking device

In order to verify the matching between the theoretical calculation results and the actual working conditions, and simulate the overturning process of the ship platform, a simulation test bench of the anti-overturning self-locking device is designed. The overturning angle and time are verified by the test bench. The design of the test bench is shown in Fig. 5.

The test bench of anti-overturning self-locking device consists of seven parts: rotating bench, self-locking device, driving rod, transparent pressure resistant shell, dial, pointer and rocker. The rotating platform can simulate the overturning process of the platform; the transparent shell contains the fixed self-locking device and driving rod, and uses transparent plastic to facilitate the observation of the experimental process; the dial, pointer and rocker can directly simulate and read the inclination angle of the ship platform.

During the experiment, the rotating handle makes the transparent pressure resistant shell and the self-locking device of the internal driving rod rotate together with the pointer. When the transparent pressure resistant shell rotates, the sliding sound of the sliding block can be heard, and the reading of the dial corresponding to the pointer is recorded, which is the overturning angle of the platform at this time. If you continue to rotate the handle, you can observe that the driving rod starts to move and record the pointer reading, which is the platform at this time Overturning angle: continue to turn the handle to make the pointer reach 180° and observe whether the ball slider locks the driving rod.

![Figure 5. Test stand for self-locking device](image-url)
5. **Experimental study on anti-overturning self-locking device**

In order to verify whether the self-locking device can successfully realize the self-locking of control rod, the sliding angle measurement of sliding block and the motion angle of driving rod in the durable shell under water and water media were carried out, which were compared with the theoretical calculation value. At the same time, the self-locking verification experiment under different rotation time was carried out to verify whether the self-locking device can realize self-locking in the process of rapid overturning of the platform.

5.1. **Experimental study on anhydrous medium**

No water is added inside the transparent and durable shell, and the anhydrous medium test is carried out. The sliding angle of the sliding block and the driving rod of the anhydrous medium is measured. The test data are recorded in Table 1.

### Table 1. Sliding angle between slide block and driving rod in anhydrous medium

| NO. | Measured angle of sliding block | Maximum angle calculated by slider | Measured angle of driving rod | Maximum angle of driving rod calculation | Lock the drive lever |
|-----|-------------------------------|-----------------------------------|-------------------------------|----------------------------------------|----------------------|
| 1   | 81°                           | 77.5°                             | 112°                          | 107.5°                                 | Y                    |
| 2   | 82°                           | 77.5°                             | 110°                          | 107.5°                                 | Y                    |
| 3   | 82°                           | 77.5°                             | 110°                          | 107.5°                                 | Y                    |
| 4   | 81°                           | 77.5°                             | 112°                          | 107.5°                                 | Y                    |
| 5   | 81°                           | 77.5°                             | 112°                          | 107.5°                                 | Y                    |
| 6   | 83°                           | 77.5°                             | 113°                          | 107.5°                                 | Y                    |
| 7   | 81°                           | 77.5°                             | 112°                          | 107.5°                                 | Y                    |
| 8   | 82°                           | 77.5°                             | 112°                          | 107.5°                                 | Y                    |
| 9   | 82°                           | 77.5°                             | 110°                          | 107.5°                                 | Y                    |
| 10  | 82°                           | 77.5°                             | 113°                          | 107.5°                                 | Y                    |

5.2. **Experimental study on water medium**

Water was added into the transparent and durable shell, and the sliding angle measurement test of sliding block and driving rod with water medium was carried out. The test data record is shown in Table 2.

### Table 2. Sliding angle of sliding block and driving rod under water condition

| NO. | Measured angle of sliding block | Measured angle of driving rod | Lock the drive lever |
|-----|-------------------------------|-------------------------------|----------------------|
| 1   | 88°                           | 118°                          | Y                    |
| 2   | 86°                           | 120°                          | Y                    |
| 3   | 87°                           | 119°                          | Y                    |
| 4   | 86°                           | 120°                          | Y                    |
| 5   | 85°                           | 120°                          | Y                    |
| 6   | 87°                           | 120°                          | Y                    |
| 7   | 86°                           | 119°                          | Y                    |
| 8   | 85°                           | 120°                          | Y                    |
| 9   | 86°                           | 118°                          | Y                    |
| 10  | 87°                           | 120°                          | Y                    |

5.3. **Self locking experiment under different overturning time**

In order to directly measure whether the self-locking device can self lock in the process of rapid overturning of the platform, the simulated rapid overturning experiments were carried out in the anhydrous medium and the water medium respectively. The handle was quickly rotated, and the
driving rod was rotated 180° at different times by stopwatch timing. The experimental results are shown in Table 3.

Table 3. Self-locking experiment of anhydrous medium under different overturning time

| NO. | Simulated overturning time | Number of repeat operations | Whether it is locked (without water) | Is it locked (with water) |
|-----|-----------------------------|-----------------------------|--------------------------------------|--------------------------|
| 1   | 5s                          | 5                           | Y                                    | Y                        |
| 2   | 4s                          | 5                           | Y                                    | Y                        |
| 3   | 3s                          | 5                           | Y                                    | Y                        |
| 4   | 2s                          | 5                           | Y                                    | Y                        |
| 5   | 1s                          | 5                           | Y                                    | Y                        |

5.4. Comparative analysis of experiments

5.4.1. Comparison of glide time between water and water. According to the experimental results, the glide angle deviation of the ball slider and the driving rod is within 5° in the water and water free state; the sliding angle of the ball slider and the driving rod in the water state is larger than that in the water free state; and the roller slider slides down before the driving rod in the water or water free state. The parameter comparison diagram is shown in Figure 6.

Figure 6. Comparison of measured angles

5.4.2. Comparison of test value and calculated value.

According to the experimental results, it can be seen that the experimental measured value of the sliding angle of the ball slider and the driving rod is larger than the maximum value calculated by theory, but the sliding time of the two is increased year on year. The parameter comparison diagram is shown in Fig. 7.

Figure 7. Comparison of test value and calculated value
5.4.3. Analysis of overturning time results. According to the experimental results, the self-locking device can realize the self-locking of the driving rod when the platform capsizes 180° in 1 second through several self-locking experiments under different overturning times; however, the time for the ship platform to overturn to 180°is much longer than 1 second, so the self-locking device can completely lock the driving rod.

5.5. Summary
Through theoretical calculation and experimental verification, the passive anti-overturning self-locking device can successfully lock the driving rod during the overturning process of the ship platform, so that the control rod does not exit from the core, so as to ensure the nuclear safety of the ship platform after capsizing.

6. Conclusion
According to the characteristics of floating nuclear power station affected by marine environment, a passive anti-overturning self-locking device is designed in this paper. On the basis of theoretical analysis, a special test bench is set up to carry out experimental research and verification with and without water. The results show that the theoretical analysis and experimental results are basically consistent, which shows that the passive self-locking device can effectively realize the locking function of the driving rod of the control rod drive mechanism of the floating reactor under the overturning state of the ship platform, so as to ensure that the control rod assembly does not exit the core and ensure the safety of the reactor. The device provides an effective and important means and measures to ensure the nuclear safety of floating nuclear power station under the condition of ship platform overturning.

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