# Research on Damping and Anti-Roll Scheme of Automatic Mooring Mechanism

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## Abstract

**This paper presents an automatic mooring mechanism with a damping-based anti-roll scheme for vessel berthing, specifically applicable to ro-ro passenger terminals. The mechanism connects to the ship's side via a telescopic arm and a suction cup, and regulates damping force through a throttle valve in the hydraulic circuit, following a quadratic damping model. Comparative analysis of roll angle responses shows that, compared with conventional mooring lines, the proposed system achieves rapid stabilization and significantly reduces the anti-roll time. Optimal damping matching is obtained at a moderate valve opening, effectively suppressing random oscillations and maintaining stable periodic motion in the steady state. The system offers a practical and efficient solution for intelligent berthing under complex sea conditions.**

## Keywords

**Automatic mooring, anti-roll, hydraulic damping, roll motion.**

## 1. Introduction

Under the action of complex marine environmental forces such as wind, waves, and swell, a vessel undergoes oscillatory motions in six degrees of freedom, namely: surge, sway, heave, roll, pitch, and yaw[1][2]. These motions often exhibit pronounced periodic characteristics, with significant nonlinear coupling among the various degrees of freedom. When a vessel is berthed at a dock, continuous external disturbances lead to irregular and non-negligible displacements and attitude changes relative to the berth, severely compromising its ability to berth stably, safely, and quickly at the intended position[3].

The typical application scenario of a ro-ro passenger terminal is particularly noteworthy[4]. Ro-ro passenger vessels feature high berthing frequency, short berth occupancy times, heavy personnel and vehicle throughput, and a wide range of vessel tonnages and types. In such a highly dynamic, high-density, and demanding operational environment, the consequences of vessel oscillations are especially severe. On one hand, excessive oscillations prolong the stabilization time after berthing, reduce terminal turnaround efficiency, and affect schedule punctuality and operational profitability. On the other hand, violent oscillations can cause fatigue fracture of mooring lines, collisions between the vessel and the dock, leading to casualties, equipment damage, and even major safety incidents. Therefore, proposing an effective and practical anti-roll control method specifically for special berths such as ro-ro passenger terminals, to suppress vessel oscillations to the greatest extent and achieve rapid stabilization, is of significant practical importance for enhancing the safety, economic efficiency, and service quality of port operations.

## 2. Operational Workflow of The Automatic Mooring Mechanism

The automatic mooring mechanism proposed in this paper is a pitch-capable telescopic arm type, with the front end equipped with a suction cup device adjustable along the quay direction. The entire machine can achieve multi-degree-of-freedom motion.

The automatic mooring mechanism works in conjunction with the dock fenders to realize automatic berthing, mooring, and unberthing operations, replacing traditional high-strength mooring line operations. The berthing process can be divided into three main stages: docking, anti-roll, and resetting.

The docking stage refers to the process where, after the vessel approaches the dock and berths, the mooring mechanism actively extends and connects to the ship's side via the end suction cup. During docking, the mooring mechanism actively controls the movement of the suction cup to the docking position. Contact between the mooring mechanism and the vessel is indicated by a feedback signal from a force sensor, following which the suction cup completes the attachment.

The anti-roll stage refers to the process where, after the suction cup connects to the ship's side, the hydraulic cylinder is switched to a damping adjustment state via a solenoid directional valve. Through different damping adjustment and control strategies, the vessel is maintained within an appropriate range of motion. During the anti-roll process, the hydraulic energy recovery circuit captures energy from the vessel's oscillations.

The resetting stage refers to the process where, after the vessel completes its operations at the dock, the mooring mechanism releases the suction cup and returns to its initial position[5].

## 3. Damping Design of The Automatic Mooring Mechanism

The mooring mechanism uses a three-position four-way solenoid directional valve to control the docking, anti-roll, and resetting operational states. During the anti-roll process of the automatic mooring device, vessel motion is primarily controlled by adjusting the damping of the mooring mechanism, keeping the vessel within a specific motion range[6].

Across the three operational stages of the mooring mechanism: during docking and resetting, the hydraulic cylinder is in an active control state, and the damping force in the branch is constant; during the anti-roll stage, the damping coefficient of the hydraulic cylinder is primarily adjusted by changing the opening of a throttle valve in the hydraulic circuit.

In analyzing the damping force during the anti-roll stage, the damping force provided by mechanical friction in the branches is neglected. The primary focus is on the damping force caused by pressure drops in the hydraulic circuit, namely, the pressure drops across the hydraulic rectifier bridge, the frictional losses along the hydraulic lines, the pressure drop across the hydraulic motor, and the pressure drop across the throttle valve. During the anti-roll stage, the damping force during cylinder compression and extension depends on the pressure difference between the cylinder's upper and lower chambers.

## 4. Study of The Anti-roll Scheme for The Automatic Mooring Mechanism

Presetting the Damping Coefficient.The throttle valve of the hydraulic system is set to a medium opening.

The convex pier-type ro-ro passenger terminal selected for this project is located in a sheltered nearshore environment with relatively favorable wave and current conditions, but experiences strong winds. Overall, the combined condition is a mixed condition with wind dominance, yet a relatively calm sea surface.

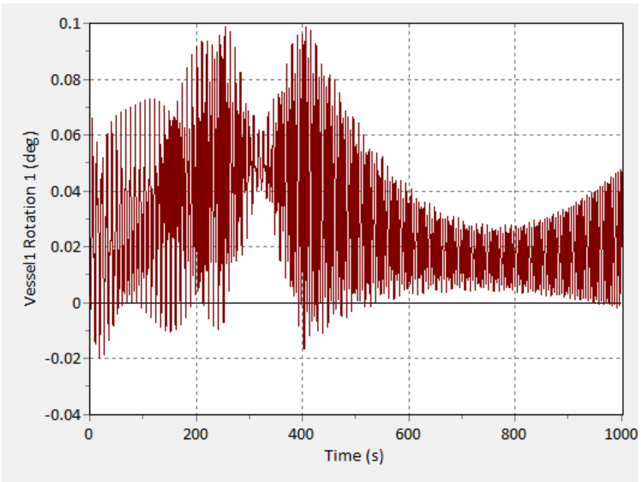
Wind speed (13.8 m/s): According to the Beaufort wind scale, 13.8 m/s is at the boundary of Force 6 (strong breeze), which has a wind speed range of 10.8–13.8 m/s.

Wave height (0.5 m): A wave height of 0.5 m typically corresponds to Sea State 2 (small wave) to Sea State 3 (slight wave) in sea state classification.

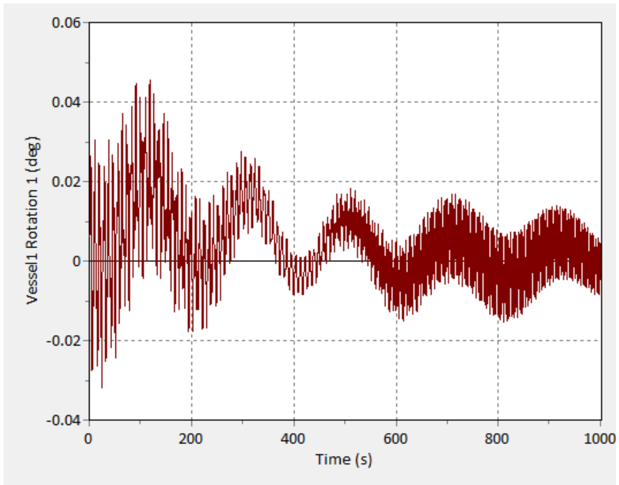
Current velocity (0.414 m/s): Approximately 0.8 knots, falling into the weak to moderate current range. A current of 0.8 knots (approximately 0.4 m/s) has a limited direct impact on vessel motion, primarily affecting vessel speed through superposition or causing displacement during navigation. In simulations, it is typically included as a background environmental disturbance factor.

The combination of the above three environmental conditions constitutes the combined condition for this calculation. Three different angular directions are selected for load application.

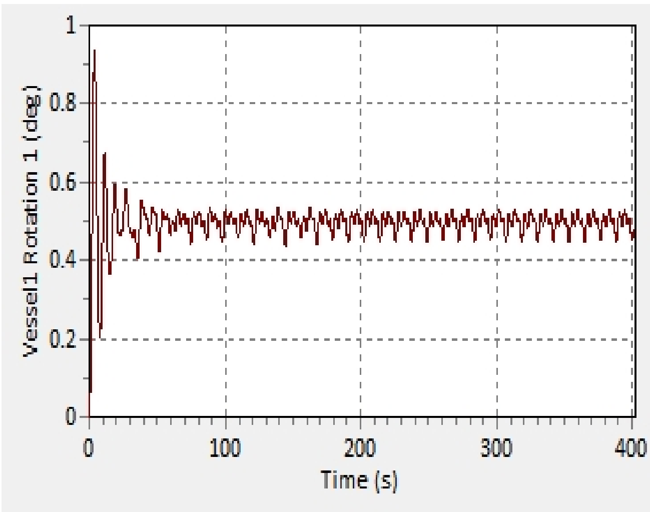
The roll angle conditions of the vessel in a free state, a moored state (conventional lines), and a state with the automatic mooring mechanism's anti-roll function are shown in the figures.




a) Free state

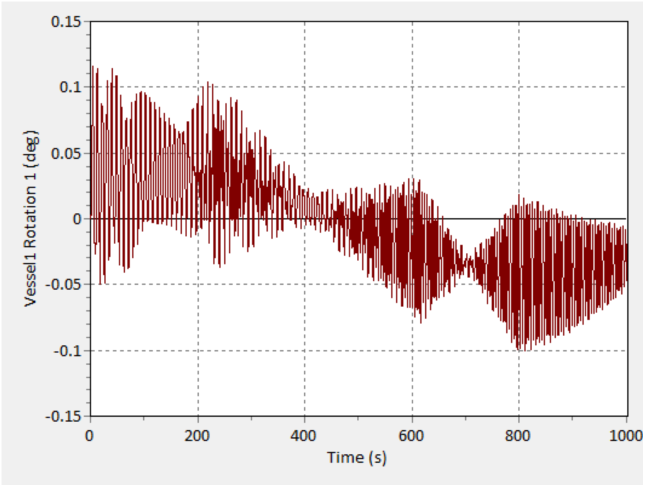



b) Moored state (conventional lines)

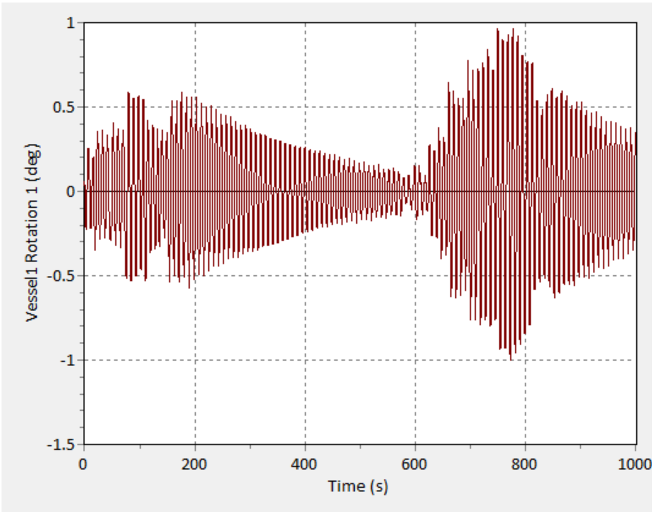



c) Anti-roll state

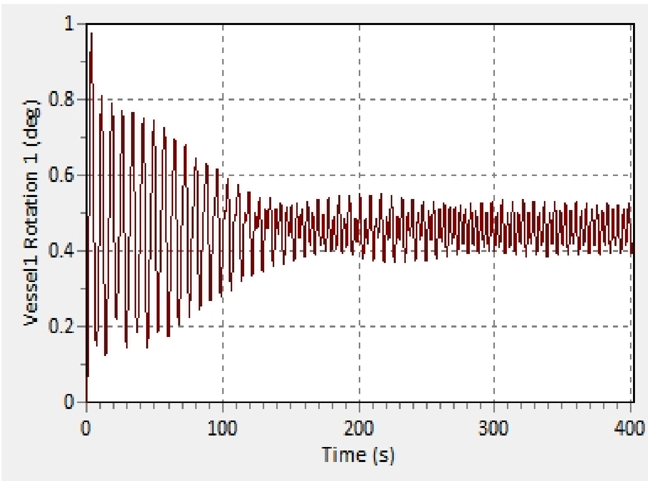
**Figure 1.** Output of roll angle (Case 1)




a) Free state

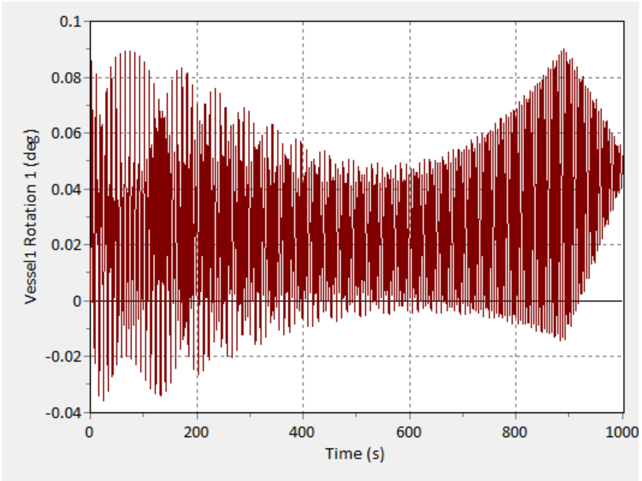



b) Moored state (conventional lines)

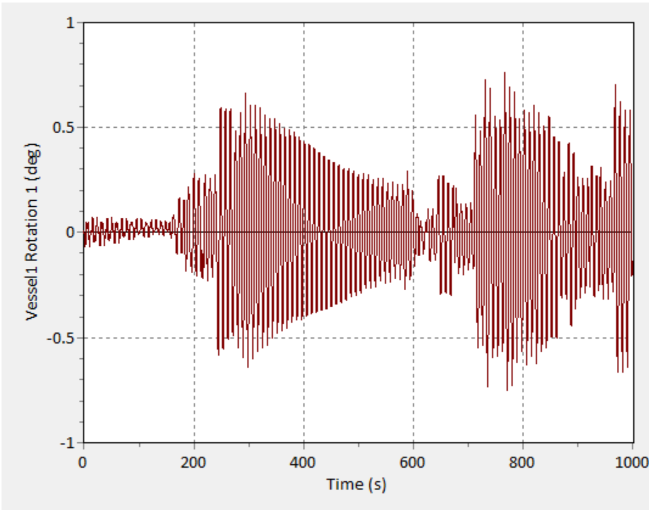



c) Anti-roll state

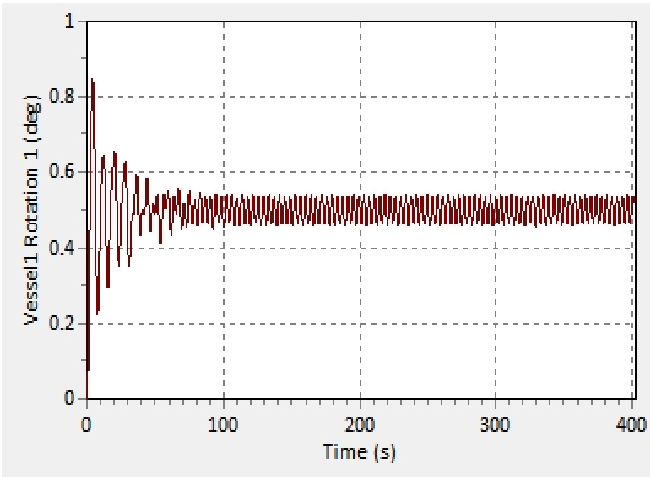
**Figure 2.** Output of roll angle (Case 2)




a) Free state




b) Moored state (conventional lines)




c) Anti-roll state

**Figure 3.** Output of roll angle (Case 3)

In free vessel state, the vessel's roll motion is non-convergent. Without any mooring constraints, the vessel is acted upon only by environmental loads such as wind, waves, and current, lacking a restoring moment and damping mechanism.

In conventional moored state, the vessel's roll motion is generally convergent, but with significant random fluctuations. The envelope of the roll angle decays slowly and is easily re-excited into large-amplitude oscillations by external disturbances. Conventional mooring is suitable only for low sea states or short-term berthing, with limited anti-roll effectiveness.

Application of the automatic mooring device (with anti-roll function). The device generates a damping force proportional to the velocity of motion by adjusting hydraulic damping elements. The time history curve of the roll angle exhibits an approximately exponential monotonic decay, with random components effectively suppressed. The time required for the roll angle envelope to decay to within 10% of its initial amplitude, from an initial large disturbance to entering a steady state, is approximately 50 seconds, significantly faster than conventional mooring. In the steady state, the roll angle is controlled within a small angular range, and the oscillations exhibit regular periodicity consistent with the dominant wave frequency, rather than random divergence.

Thus, the damping system of the automatic mooring mechanism proposed in this paper achieves rapid and stable anti-roll effects, making it suitable for intelligent berthing under complex sea conditions.

## 5. Motion Response Analysis

When the throttle valve opening is excessively large, i.e., under the condition of excessive opening, the throttling gap increases significantly, allowing oil flow to proceed almost unimpeded, resulting in insufficient damping and loss of anti-roll function. Under this condition, the damping force generated by the hydraulic cylinder is far below the system's load capacity, placing the system in a severely underdamped state. In this operational scenario, the vessel's roll motion exhibits typical low-damped oscillatory characteristics: the amplitude of the roll angle decays extremely slowly, resulting in a prolonged convergence time. Following each wave excitation, the vessel requires multiple successive oscillations before gradually approaching equilibrium, with a relatively large steady-state roll angle amplitude and pronounced random fluctuation components. Under this valve opening, the automatic mooring device fails to effectively perform its anti-roll function, providing only very limited energy dissipation. Therefore, a large valve opening is only suitable for very low sea states, temporary berthing without anti-roll requirements, or equipment commissioning, and is not recommended for routine operational conditions.

When the throttle valve opening is excessively small, i.e., under the condition of insufficient opening, the throttling gap is compressed to a minimum, generating extremely high local resistance as oil passes through, leading to excessive damping and rigid impact. The damping force increases quadratically. Even at very low piston velocities, the damping force may exceed the rated load capacity of the hydraulic cylinder, causing the system to tend toward overdamping or even approach hydraulic lock. Although the vessel's roll motion can converge quickly under this condition, it comes at the cost of a series of adverse effects: first, the hull's response to wave excitation becomes severely lagged, with the roll motion becoming phase-shifted relative to the waves, potentially inducing high-frequency buffeting; second, the pressure differential across the throttle valve rises abruptly, resulting in impact spikes at the fixed-end reaction forces, which may cause fatigue in the hydraulic lines or overload the sensors; third, localized overheating of the hydraulic fluid and increased noise occur, potentially leading to cavitation in severe cases. Under this valve opening, the mooring device degrades from an anti-roll device to a rigid constraint, behaving more like a mechanical lock than a dynamic damper. This setting is only applicable for emergency protection under extremely harsh sea conditions and is not suitable for prolonged operation.

When the throttle valve opening is adjusted to a moderate range, i.e., under the condition of moderate opening, the system achieves optimal damping matching and ideal anti-roll performance. Under this condition, the damping force exhibits an appropriate quadratic relationship with the vessel's roll velocity, generating a reasonable damping force under typical velocities, accounting for approximately 75% of the load capacity. With these parameters, the roll angle curve exhibits a regular exponential decay pattern, with random components effectively suppressed. Under ideal conditions, convergence to steady state is achieved within 50 seconds. Once steady state is reached, the roll angle is maintained within a small angular range, and the oscillations exhibit a regular periodic waveform. Simultaneously, the fixed-end reaction forces attenuate synchronously, with the force differential between the nearshore and offshore side devices remaining within physically expected limits and devoid of impact spikes. This valve opening achieves the three primary objectives of rapid convergence, stable small-angle oscillation, and controllable impact, representing the recommended operating point for the anti-roll system. In practical commissioning, it is suggested that this setting be used as the initial baseline, with fine adjustments made according to specific sea conditions, thereby satisfying the anti-roll requirements for the vast majority of berthing operations.

## 6. Structural Strength Verification

Based on the above damping anti-roll scheme, the strength and stiffness of the automatic mooring mechanism are verified to determine whether they meet the operational requirements.

The boundary conditions for the extreme case are defined as follows.

The mooring unit can withstand a maximum tensile force of 200 kN in the quay-normal direction (i.e., perpendicular to the dock shoreline) and a maximum tensile force of 100 kN in the quay-parallel direction (i.e., parallel to the dock shoreline). These values are derived from the most unfavorable load combination under the combined action of extreme wind, wave, and current conditions, ensuring that the mooring unit does not suffer structural failure or permanent deformation under severe sea states exceeding the design return period. When the external load approaches the above thresholds, the system shall trigger an alert and activate a backup safety mechanism.

A rigid connection is adopted between the bottom of the mooring unit and the wharf structure, which is configured as a full six-degree-of-freedom constraint (i.e., all three translational degrees of freedom and three rotational degrees of freedom are fixed). This means that no relative displacement or rotation occurs at the bottom of the mooring unit during loading, ensuring reliable load transfer to the wharf foundation and preventing mooring failure due to connection loosening or misalignment. This constraint condition applies to all normal and extreme operating conditions.

When the displacement in any direction exceeds the preset safety threshold of the mooring unit, the system automatically determines an "unstable suction" state and immediately performs a rapid suction cup release action. The attitude of the mooring device is adjusted, the suction cup automatically reattaches to the hull surface, and the mooring force transmission is restored.

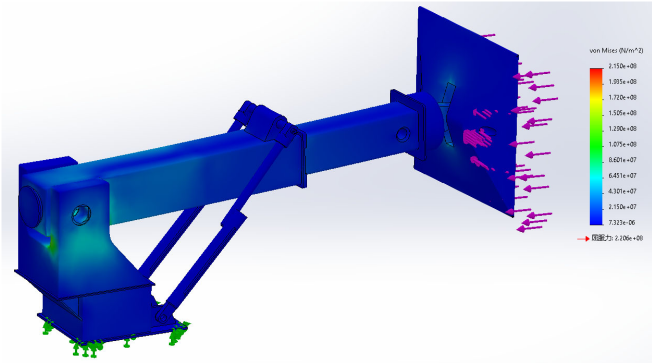



**Figure 4.** Structural strength verification

The finite element analysis results are shown in the figure, confirming that the structural strength requirements are satisfied.

## 7. Research Outlook

Current research primarily relies on numerical simulations and laboratory experiments, lacking support from full-scale, real-sea-state measurement data. The second-generation prototype of the automatic mooring unit developed by our institute is scheduled to undergo full-scale vessel mooring trials. The trial contents include: reliability testing of suction cup attachment and release under different tidal levels and wind-wave conditions; measurement of the actual roll suppression effectiveness of the damping valve opening; dynamic strain monitoring of key components of the mooring unit (including the support transition section, telescopic arm sliding interface, and anchor bolts); and vibration response analysis of the wharf foundation under cyclic loading. Furthermore, long-term continuous operation tests (e.g., over an actual operational period of more than three months) will be conducted to record reliability indicators such as suction cup wear, providing a basis for product finalization and the formulation of maintenance procedures.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