Proceedings of the Thirty-sixth (2026) International Ocean and Polar Engineering Conference **www.isope.org**
Orlando, Florida, USA, May 31-June 5, 2026

ISBN 978-1-880653-72-2; ISSN 1098-6189

Control Study of a Floating Offshore Wind Turbine Platform Based on a Gyroscopic Stabilizer

Ping Cheng[1,2], Tingyuan Zhang[1], Wenchuan Zhao[1], Decheng Wan[2]*

[1] College of Logistics Engineering, Shanghai Maritime University, Shanghai, China
[2] Computational Marine Hydrodynamics Lab (CMHL), School of Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai, China
[*]Corresponding author

ABSTRACT

A gyroscopic stabilizer suppresses the pitch motion of a floating offshore wind turbine platform by generating a counteracting moment through real-time regulation of the rotor precession angle. This study investigates its working mechanism and active control principle and proposes an adaptive fuzzy PID control strategy integrated into a closed-loop platform motion control system. Using pitch-angle measurements from attitude sensors, the controller adaptively adjusts the PID parameters to regulate the rotor precession angle, thereby achieving active control with a short response delay, low inertia effects, and minimal overshoot. Numerical simulations in MATLAB were used to compare the proposed method with the conventional PID control under various sea states. The results show that the adaptive fuzzy PID controller provides a faster dynamic response, smaller overshoot, and stronger disturbance rejection, thereby achieving significant pitch reduction under different conditions. The pitch suppression efficiency depends on the rotor speed and sea state, with a greater reduction observed at increased rotor speeds and in longer-period waves.

KEY WORDS: gyroscopic stabilizer; Floating Offshore Wind Turbine Platform; fuzzy PID controller; active control; Numerical Simulations in MATLAB.

INTRODUCTION

With the increasing scarcity of nonrenewable energy resources, renewable energy sources such as wind power have become strategically significant. Offshore wind power offers considerable advantages over onshore wind turbines. Floating offshore wind turbines (FOWTs) are key technologies for deep- and ultra-deep-sea wind energy development, in which wind and wave loads can induce rolling and pitching motions. These irregular motions not only compromise the platform stability and wave resistance, but also adversely affect their hydrodynamic performance (Ou et al., 2006). Compared to conventional offshore structures, FOWT platforms are large-scale and possess distinctive structural and dynamic characteristics. Under wind and wave excitations, they are prone to severe oscillations that exacerbate the fatigue loads on the system. Under extreme sea conditions, excessive pitch motion may cause platform flooding or capsizing, posing serious safety risks. Effectively suppressing the pitch motion of FOWT platforms can enhance power generation efficiency, operational safety, and durability(Yin et al., 2022). Therefore, it is essential to develop control strategies to mitigate the pitch motion of FOWT platforms(ZHANG et al., 2025).

Conventional roll and pitch mitigation measures, such as ballast tanks, tuned mass dampers, and mooring chains, must be incorporated during the initial design stage of an FOWT. Implementing such mitigation solutions is often challenging and incurs high retrofitting costs for platforms that have already been deployed and are in operation. As emerging stabilization devices, gyroscopic stabilizers have attracted considerable attention owing to their suitability for retrofitting existing FOWTs. Gyroscopic stabilizers are already widely applied in maritime and aerospace fields, offering a practical approach to enhancing platform stability without major structural modifications(J. Wang et al., 2015).

Under external disturbances, a gyroscopic stabilizer installed on a FOWT generates precession through its high-speed rotor, producing a control moment opposite to the platform motion, thereby suppressing the pitch motion of the platform. Depending on whether control of the precession angle is incorporated, gyroscopic stabilizers can be classified into passive and active types. Early gyroscopic stabilizers primarily operated passively, with their roll and pitch reduction performances limited by the inherent structure of the gyroscope. In 1911, the American company Sperry introduced a forced precession mechanism into a conventional passive gyroscope, resulting in an active gyroscopic stabilizer. This device was installed on a yacht in 1915, and subsequent trials demonstrated its effectiveness in suppressing the vessel motion(Lu & Chen, 2011).

In recent years, the active control capabilities of gyroscopic stabilizers have continuously improved with the rapid development of new technologies, advanced materials, and manufacturing processes. By integrating sensors and controllers, the motion states of an FOWT platform can be sensed in real time and the feedback can be adjusted, making the stabilization system more flexible and efficient. However, in complex and variable marine environments, conventional control strategies are often limited in terms of control accuracy and disturbance rejection. Although conventional proportional-integral-derivative (PID) controllers are simple and easy to implement, a fixed set of PID parameters is insufficient to cope with highly dynamic wave disturbances, and the system performance deteriorates under extreme sea conditions. By contrast, fuzzy control can perform rule-based reasoning and parameter adjustment according to the system state, offering distinct advantages. Combining fuzzy control with PID control to form a fuzzy PID control strategy improves the stabilization performance while maintaining both control accuracy and disturbance rejection(S. Wang et al., 2011). For example, Qie et al.(QIE et al., 2025) proposed a GA-based parameter optimization method. By performing refined modeling and numerical simulations of the gyroscopic stabilizer system, the optimized system achieved a roll and pitch reduction efficiency of 97.44% under sea state 4 while effectively suppressing the oscillations induced by precession damping and significantly enhancing the performance of the stabilizer. Inspired by the operating principle of passive gyroscopes, Song et al.(Song et al., 2023) conducted experiments using attitude sensors to measure vessel motion at different sampling frequencies and applied angular rate feedback control combined with a PID algorithm to regulate the precession motion and achieve effective roll reduction for ship models. Similarly, Qi et al.(Qi et al., 2018) designed a fuzzy-immune PID gyroscopic control device to study the stabilization performance at low sailing speeds, demonstrating improved motion suppression in relation to passive gyroscopes under random wave conditions. Currently, gyroscopic stabilizers are widely applied in the maritime and aerospace fields; however, research on the active control of gyroscopic stabilizers for FOWT platforms remains relatively limited. In this study, the active control of a gyroscopic stabilizer installed on a FOWT was investigated using multibody dynamic modeling and numerical simulations, focusing on the effects of incorporating fuzzy control, varying sea conditions, and rotor speed on the stabilization performance.

SYSTEM CONFIGURATION AND STABILIZATION MECHANISM

Compared with other angular motions of a FOWT, the pitch motion poses more severe risks owing to variations in the angle of attack, dynamic stall effects, and low-frequency amplification. Under harsh sea conditions, excessive pitch motion can significantly affect both the structural safety of FOWT and the stability of power generation. Therefore, the pitch performance of a FOWT platform is a critical indicator for evaluating its overall operational performance.

As shown in Fig. 1, the entire FOWT system can be decomposed into two main subsystems: the upper wind turbine and tower structure, and the lower floating support platform. Given the high complexity of the FOWT system, and considering that the pitch motion of the floating wind turbine is primarily induced by wave excitation acting on the supporting platform, this study focuses on the dynamic response of a floating support platform under wave loads. Therefore, the influences of the upper wind turbine and tower structure on the pitch motion are neglected in the present analysis (Yang, 2024).

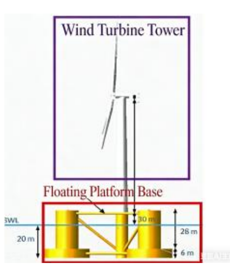


Fig.1. OC4 FOWT.

The mathematical model of the pitch motion of a floating offshore wind turbine platform is presented below:

$$(I_{XX} + I'_{XX})\ddot{\varphi} + A(\dot{\varphi}, \varphi) + B(\varphi) = M_w - M_g \tag{1}$$

where I_{XX} denotes the mass moment of inertia of the floating wind turbine platform, I'_{XX} represents the added mass moment of inertia associated with the pitch motion, $\ddot{\varphi}$ corresponds to the pitch angular acceleration of the platform, $A(\dot{\varphi}, \varphi)$ is the hydrodynamic damping moment acting on the pitch motion, $B(\varphi)$ denotes the restoring moment of the pitch motion, $\dot{\varphi}$ is the pitch angular velocity of the platform, M_w represents the random wave excitation moment acting on the platform, and M_g represents the gyroscopic stabilizing moment.

In this study, the hydrodynamic coefficients are obtained using CFD simulations performed in STAR-CCM+.

The stabilizing moment generated by the gyroscopic stabilizer can be expressed as follows:

$$M_g = I \cdot \omega \cdot \omega_p \tag{2}$$

where I denotes the spin moment of inertia of the gyroscopic rotor, ω the spin angular velocity of the gyroscope, and ω_p the precession angular velocity of the gyroscope(L. Wang, 2021; Zhu, 2020).

A gyroscopic stabilizer suppresses motion by exerting a stabilizing moment on a FOWT through a high-speed rotating rotor. In the fully coupled wave–FOWT–controller–gyroscopic stabilizer system, the stabilization effect is primarily realized through the angular momentum generated by the high-speed rotor. The control system adaptively adjusts the PID parameters in real time based on fuzzy rules, enabling the controller to precisely regulate the gimbal rotation angle. Thus, both the direction and magnitude of the rotor-generated moment can be controlled such that the output moment acts in opposition to the pitch moment of the FOWT, thereby effectively reducing platform oscillations.

CONTROL SYSTEM DESIGN

PID Control Design

The core of active control for a gyroscopic stabilizer lies in the application of an external control moment to regulate both the magnitude and direction of the stabilizing moment. Applying an external moment to the gyroscopic stabilizer is equivalent to imposing a corresponding input angular velocity on the precession axis. The stabilization performance of a gyroscopic stabilizer depends on its inherent moment of inertia, spin angular velocity, and precession angular velocity. The moment of inertia of the rotor was fixed during the design stage, and the spin speed became constant once the rotor operated stably. Under these conditions, with the moment of inertia and spin speed remaining unchanged, the magnitude of the stabilizing moment can only be adjusted by varying the precession angular velocity. Regarding the control of the moment direction, the stabilizing moment was fully effective in counteracting the pitch motion only when the spin axis was perpendicular to the FOWT platform. If precession causes the spin axis to tilt, the resulting stabilizing moment has components along the roll and yaw axes, which may affect the overall platform stability and power generation efficiency. Therefore, the precession angle was controlled based on the error between the ideal and actual pitch angles. The control strategy effectively regulates the precession angular velocity according to the pitch rate by exploiting the relationship between the pitch and precession angles. This approach allows for both a small precession angle and precise adjustment of the precession angular velocity, thereby simultaneously controlling the magnitude and direction of the stabilizing moment.

Based on the above analysis, the control equation introduced into the system can be expressed as follows:

$$\beta = -K_p\varphi - K_i\int_0^t \varphi dt - K_d\dot{\varphi} \quad (3)$$

where β denotes the target precession angle of the gyroscopic stabilizer, φ represents the pitch angle of the FOWT platform, and K_p, K_i, and K_d correspond to the externally applied proportional, integral, and derivative control components, respectively.

Fuzzy PID Control Design

The practical analysis of a conventional PID controller for regulating the pitch angle of a FOWT platform has several limitations, including slow response, overshoot, and poor disturbance rejection, which make it difficult to cope with complex sea states in deep and ultra-deep waters. The fuzzy PID control designed in this study is based on a traditional PID controller. By performing fuzzy analysis of the system, the controller computes real-time corrections to the PID parameters and adaptively tunes them based on fuzzy rules and expert knowledge(Z. Wang & Xu, 2025). This approach enables efficient and reliable control, overcomes the shortcomings of conventional PID methods, and achieves precise and rapid adjustment of the precession angle of the gyroscopic stabilizer, thereby effectively suppressing the pitch motion of the FOWT platform.

The gyroscopic stabilizer control system integrates fuzzy rules into a PID controller. When the pitch angle of the FOWT changes, the fuzzy PID controller automatically adjusts the PID parameters, achieving active control with short response delay, low inertia effects, and minimal overshoot. The structure of the self-tuning PID control system for the FOWT gyroscopic stabilizer is shown in Fig. 2.

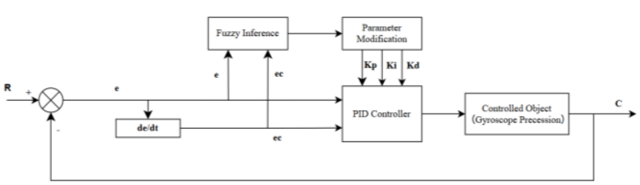


Fig.2. Structure Diagram of the Fuzzy Self-Tuning PID Control System.

When performing stabilization, the gyroscopic stabilizer control system must consider not only the adjustment range of the FOWT platform's pitch angle but also the system's inertia and nonlinearity. Angle adjustments should be smooth, and the control response should not be excessively delayed. The designed adaptive fuzzy PID control system operates as follows. Based on the platform's pitch angle, the pitch error e and the rate of change of the pitch error ec are analyzed. These values were then fuzzified and fed into the fuzzy controller, which generated the adjustment quantities ΔK_p, ΔK_i, and ΔK_d. After parameter calculation, the corrected PID parameters K_p, K_i, and K_d were obtained and input into the PID controller. The controller then calculated the precession angle of the gyroscopic stabilizer required to suppress the pitch motion of the FOWT. By controlling the gyroscopic stabilizer accordingly, the system effectively stabilized the FOWT platform(YU & Yang, 2018).

Variable and Universe of Discourse Design

(a)

(b)

(c)

(d)

(e)

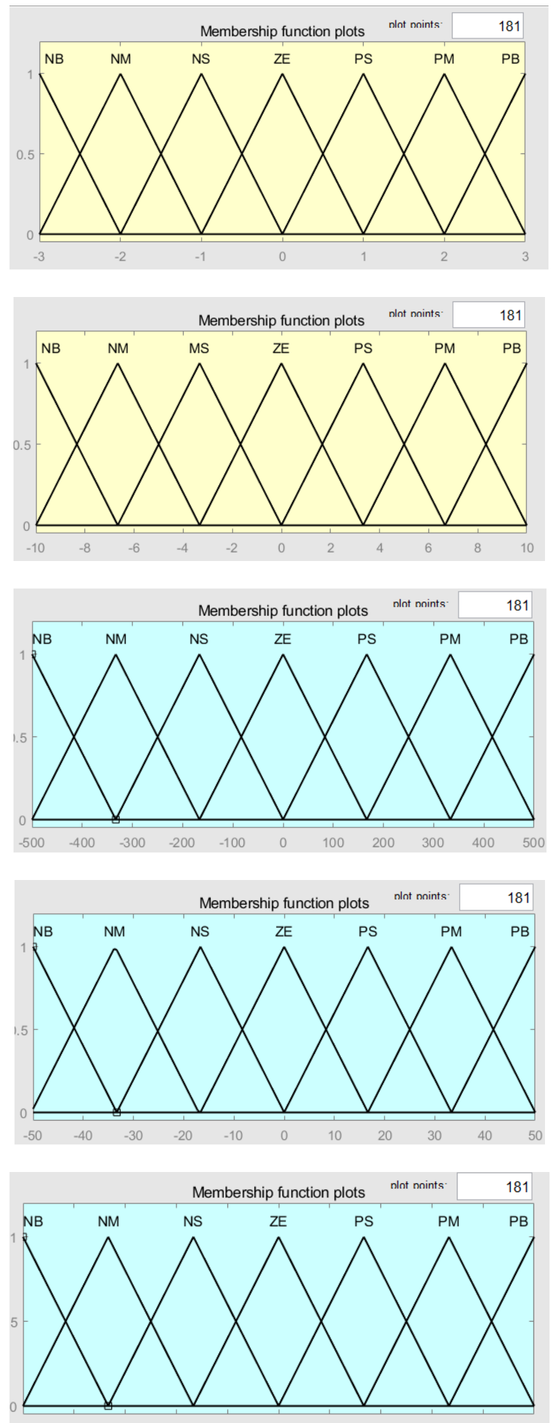


Fig.3. (a) Membership Function of e (b) Membership Function of ec (c) Membership Function of ΔK_p (d) Membership Function of ΔK_i (e) Membership Function of ΔK_d

Based on the requirements of the stabilization control system, the basic universe of discourse for the pitch error e and the rate of change of the pitch error ec are defined as[-3,3] and [-10,10], respectively. The basic universe of discourse for the control parameters ΔK_{p}, ΔK_{i}, and ΔK_{d} is set to [-500,500], [-50,50], and [-5,5], respectively. Following the standardization methodology proposed by Mamdani, a set of fuzzy subsets {NB,NM,NS,ZE,PS,PM,PB}is defined, corresponding to negative big, negative medium, negative small, zero, positive small, positive medium, and positive big, respectively. The pitch error e is defined as the difference between the desired value and the measured value, and the rate of change of the pitch error is given by $\frac{\mathrm{de}}{\mathrm{dt}}$.

In fuzzy control, to achieve a balance between response speed and control accuracy, standard triangular membership functions are adopted to fuzzify the pitch error e and its rate of change of pitch error ec. The fuzzy inference system takes the error e and error change rate ec as input variables and outputs the control increments ΔK_{p}, ΔK_{i}, and ΔK_{d} based on predefined fuzzy rules(Yan et al., 2024). The membership functions of the input and output variables of the fuzzy controller are shown in Fig. 3.

Establishing the Fuzzy Control Rule Base

Fuzzy PID control rules are established based on an in-depth understanding of classical control theory combined with artificial experience and learning mechanisms. These fuzzy rules are employed to realize online self-tuning of the PID control parameters. The fundamental design principles are summarized as follows(Lin et al., 2013).

When the absolute value of the error $|e|$ is large, a relatively large proportional gain K_{p} should be adopted to accelerate the system response, whereas a smaller integral gain K_{i} should be selected to prevent an excessive overshoot. A smaller derivative gain K_{d} was used to avoid noise amplification.

When the absolute value of the error $|e|$ is moderate, the proportional gain K_{p} should be reduced to balance the response speed and system stability, thereby lowering the risk of overshoot. The integral gain K_{i} was appropriately adjusted to improve the control accuracy, and a smaller derivative gain K_{d} was employed to limit its influence on the system.

When the absolute value of the error $|e|$ is small, a smaller proportional gain K_{p} is selected to ensure the system stability, whereas a larger integral gain K_{i} is used to reduce the steady-state error. An appropriate derivative gain, K_{d} is chosen to suppress the oscillations and enhance the disturbance rejection capability of the system.

When the absolute value of the error change rate $|ec|$ is large, a smaller proportional gain K_{p} should be applied to avoid an excessive system response.

When the absolute value of the error change rate $|ec|$ is small, a larger proportional gain K_{p} is adopted to accelerate the convergence and improve the control sensitivity.

Table 1. Fuzzy Adjustment Rule Table of ΔK_p

ΔK_p		Error Variation Rate (e)						
		NB	NM	NS	ZE	PS	PM	PB
Motion Error (e)	NB	PB	PB	PM	PM	PS	ZE	ZE
	NM	PB	PM	PM	PS	ZE	ZE	NS
	NS	PM	PM	PS	ZE	NS	NM	NM
	ZE	PM	PS	ZE	ZE	ZE	NS	NM
	PS	NM	NS	ZE	ZE	PS	PM	PM
	PM	NS	ZE	ZE	PS	PM	PM	PB
	PB	ZE	ZE	PS	PM	PM	PB	PB

Table 2. Fuzzy Adjustment Rule Table of ΔK_i

ΔK_i		Error Variation Rate (e)						
		NB	NM	NS	ZE	PS	PM	PB
Motion Error (e)	NB	NB	NB	NM	NM	NS	ZE	ZE
	NM	NB	NM	NM	NS	ZE	ZE	PS
	NS	NM	NM	NS	ZE	PS	PM	PM
	ZE	NM	NS	ZE	PS	ZE	NS	NM
	PS	PM	PM	PS	ZE	NS	NM	NM
	PM	PS	ZE	ZE	NS	NM	NM	NB
	PB	ZE	ZE	NS	NM	NM	NB	NB

Table 3. Fuzzy Adjustment Rule Table of ΔK_d

ΔK_d		Error Variation Rate (e)						
		NB	NM	NS	ZE	PS	PM	PB
Motion Error (e)	NB	PS	PM	PM	PB	PM	PM	PS
	NM	PS	PM	PB	PB	PB	PM	PS
	NS	ZE	PS	PM	PM	PM	PS	ZE
	ZE	ZE	ZE	PS	ZE	PS	ZE	ZE
	PS	ZE	PS	PM	PM	PM	PS	ZE
	PM	PS	PM	PB	PM	PB	PM	PS
	PB	PS	PM	PM	PB	PM	PM	PS

According to the fuzzy control principles described above, the fuzzy control rule tables for the outputs ΔK_{p}, ΔK_{i}, and ΔK_{d} of the fuzzy PID controller were obtained, as presented in Tables 1, 2, and 3(Hu et al., 2017). The fuzzy control rules constitute the core of the entire fuzzy controller, and the rule inference is implemented using conditional

statements of the form “if A, then B”(Ji & Sun, 2018). By establishing a systematic fuzzy control rule base for the gyroscopic stabilizer, a solid foundation is provided for the adaptive tuning and real-time correction of the PID controller parameters, thereby enabling effective active roll reduction of the FOWT platform(Z. Wang, 2021).
The integral term is introduced gradually only when the pitch-angle error approaches zero, and its rate of change remains small to avoid the induction of low-frequency oscillations under wave excitation. The design objective of the fuzzy PID controller is to improve the steady-state control accuracy without excessively degrading the dynamic performance of the system. Based on the instantaneous values of the pitch error e and its rate of change ec, the control increments ΔK_{p}, ΔK_{i}, and ΔK_{d} are adaptively adjusted over time, thereby ensuring favorable static and dynamic control performance of the overall system.

Defuzzification

Because the controller outputs the fuzzy increments ΔK_{p}, ΔK_{i}, and ΔK_{d},these values cannot be used directly to control the precession of the gyroscopic stabilizer. Therefore, it is necessary to convert these fuzzy increments into precise numerical values that can be directly applied. Defuzzification is performed using the centroid method to convert the fuzzy increments into crisp values, which are then used for real-time adjustment of the PID parameters. The discrete calculation formula is as follows:

$$\mu = \frac{\sum \mu(\mathrm{u_i}) \cdot \mathrm{u_i}}{\sum \mu(\mathrm{u_i})} \tag{4}$$

In the above formula, u_i and $\mu(u_i)$ denote the centroid and membership value of the symmetric membership function, respectively, and μ represents the defuzzified output value.

$$\begin{cases} K_p = K_{p0} + \Delta K_p \\ K_{\mathrm{i}} = K_{\mathrm{i}0} + \Delta K_{\mathrm{i}} \\ K_d = K_{d0} + \Delta K_d \end{cases} \tag{5}$$

The symbols $K_{\mathrm{p}0}$, $K_{\mathrm{i}0}$, and $K_{\mathrm{d}0}$ correspond to the initial values of the fuzzy PID controller parameters.

Fuzzy System Simulation

In the fuzzy system, the pitch angle error e and the rate of change of the pitch error ec are used as input signals to the fuzzy PID logic controller. Fuzzification is performed using the Mamdani inference method, and defuzzification is performed using the centroid method. The fuzzy inference outputs, denoted as ΔK_{p}, ΔK_{i}, and ΔK_{d}, are obtained, as illustrated in Fig. 4.

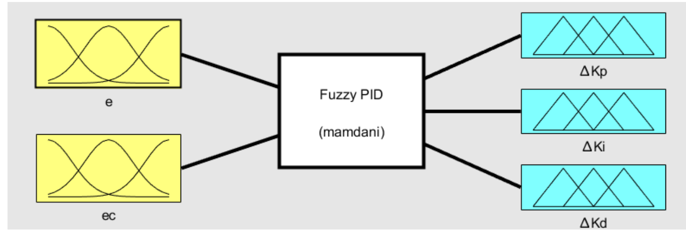
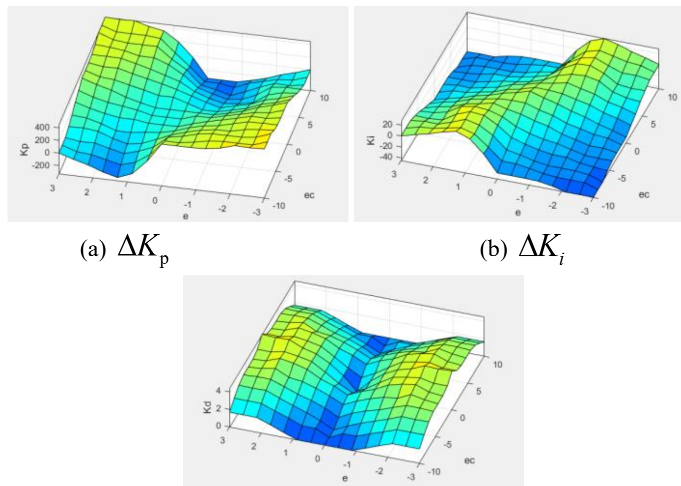


Fig.4. Structure of Fuzzy Inference.

The fuzzy rules for the output variables are implemented programmatically using conditional statements. For example: if $e = NB$ and $ec = NB$,then $\Delta K_{\mathrm{p}} = PB$, $\Delta K_{\mathrm{i}} = NB$, and $\Delta K_{\mathrm{d}} = PS$ .Based on the rule base of the fuzzy controller, the fuzzy inference surface can be generated, as shown in Fig. 5. The surface is observed to be smooth and continuous, without any breaks or abrupt jumps, indicating that the fuzzy rules have been properly formulated.



(a) ΔK_{p} (b) ΔK_i

(c) ΔK_d

Fig.5. Surface Observation Plot.

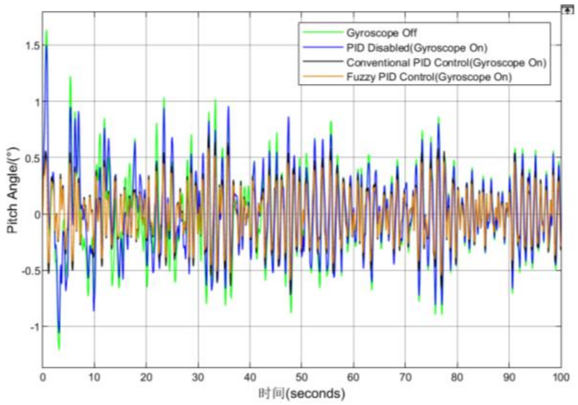
ADAPTIVE FUZZY CONTROL SIMULATION AND ANALYSIS

Table 4. Parameters of the FOWT Platform Before and After Scaling.

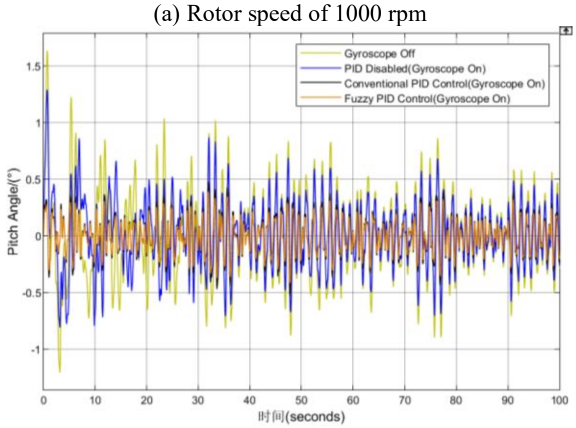
Parameters	Prototype	Model
Mass/kg	1.3958×107	111.64
Distance from Center of Mass to Water Surface/m	8.07	0.161
Pitch Moment of Inertia/kg·m^2	1.5552×1010	49.76

In this study, simulations of a floating offshore wind turbine (FOWT) platform equipped with a gyroscopic stabilizer and an active fuzzy PID controller were conducted using MATLAB/Simulink(Jiang, 2011; LIU et al., 2022). Considering the applicability of the gyroscopic stabilizer to the FOWT, a 1:50-scale model of the OC4 floating platform was selected for the simulations. The FOWT parameters before and after scaling are listed in Table 4. The stabilization performance of the platform with the fuzzy PID-controlled gyroscopic stabilizer was compared with that of three other cases: (1) a platform without a gyroscopic stabilizer, (2) a platform with a gyroscopic stabilizer operating without controller activation, and (3) a platform with a conventional PID controller.

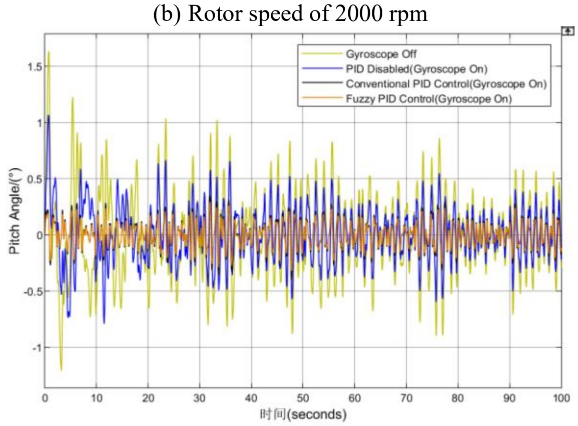
Stabilization Performance of the Gyroscopic Stabilizer at Different Rotor Speeds



(a) Rotor speed of 1000 rpm



(b) Rotor speed of 2000 rpm



(c) Rotor speed of 3000 rpm

Fig.6. Time-Domain Responses of Floating Wind Turbine Pitch Motion under Different Rotor Speeds.

Based on typical North Sea conditions, the significant wave heights and peak wave periods corresponding to moderate sea conditions are h = 6.0 m and T =10.0 s, respectively. According to the Froude similarity criterion, these values are scaled to h = 0.12 m and T =1.414 s. Figure 6 illustrates the time-domain responses of the platform pitch motion under different rotor speeds and control strategies of the gyroscopic stabilizer (the rotor speed is set to 0 when the gyroscope is deactivated). As shown in the figure, the pitch motion exhibits the largest amplitude when the gyroscopic stabilizer is inactive. After activating the gyroscopic stabilizer, the suppression of the platform pitch motion was progressively enhanced under passive and conventional PID control. The smallest pitch amplitude is achieved when the fuzzy PID control strategy is adopted. Moreover, as the rotor speed increased, the stabilization performance of the gyroscopic stabilizer improved. When the rotor speed reached 3000 rpm, the fuzzy PID-controlled gyroscopic stabilizer demonstrated superior pitch reduction performance compared to the other control strategies.

As shown in Figure 7, with increasing rotor speed of the gyroscopic stabilizer, the mean pitch amplitude of the FOWT platform decreases continuously, whereas the corresponding pitch reduction ratio increases accordingly. The introduction of conventional PID control and fuzzy PID control further enhanced the stabilization performance. Under conventional PID control, when the rotor speed reaches 3000 rpm, the mean pitch amplitude of the platform decreases to 0.0966°, corresponding to a pitch reduction ratio of 68%. By contrast, under fuzzy PID control at the same rotor speed, the mean pitch amplitude decreased to 0.0865°, and the pitch reduction ratio increased to 71%. The simulation results indicated that the fuzzy PID controller consistently exhibited superior stabilization performance across different rotor speeds, achieving an improvement of approximately 5% in the pitch reduction ratio.

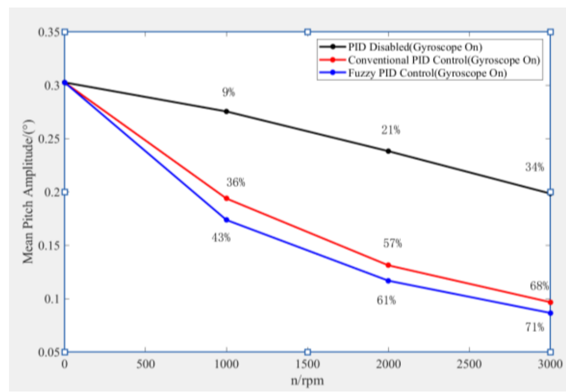
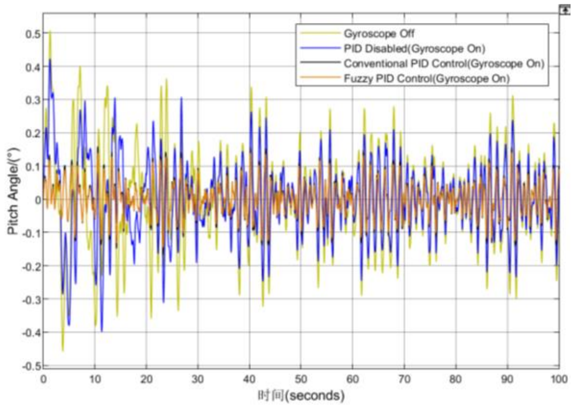


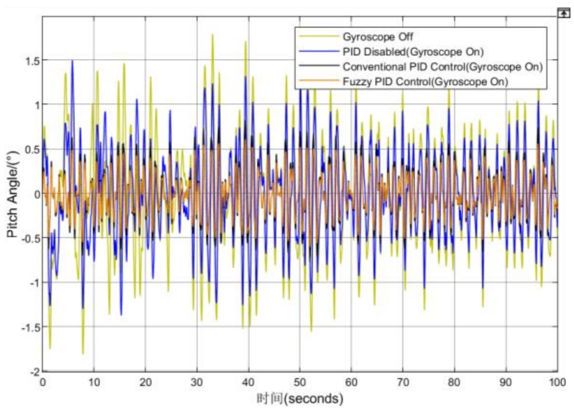
Fig.7. Stabilization Performance of the Gyroscopic Stabilizer under Different Rotor Speeds.

Stabilization Performance of the Gyroscopic Stabilizer under Different Wave Heights

Under the condition of a wave period of T =10.0 s, wave heights of h = 2 m, 6 m, and 10 m are selected to represent calm, moderate, and extreme sea states in the North Sea, respectively. Based on the Froude similarity criterion, the scaled wave period and wave heights are T =1.414 s and h = 0.04 m, 0.12 m, and 0.2 m. Figure 8 shows the time-domain responses of the platform pitch motion under different wave heights and control strategies of the gyroscopic stabilizer, with the rotor operating at the rated speed of 2000 rpm. As illustrated in the figure, the pitch motion exhibited the largest amplitude when the gyroscopic stabilizer was deactivated. Both conventional and fuzzy PID controls provide effective pitch reduction, with the smallest pitch amplitude achieved under fuzzy PID control. Moreover, as the wave height increased, the effectiveness of the gyroscopic stabilizer gradually increased. The time-domain responses at a wave height of h = 0.12 m is shown in Figure 6(b).



(a) Wave Height of 0.04 m



(b) Wave Height of 0.2 m

Fig.8. Time-Domain Responses of Floating Wind Turbine Pitch Motion under Different Wave Heights

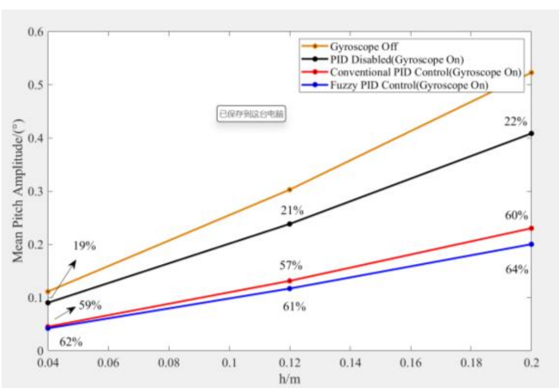
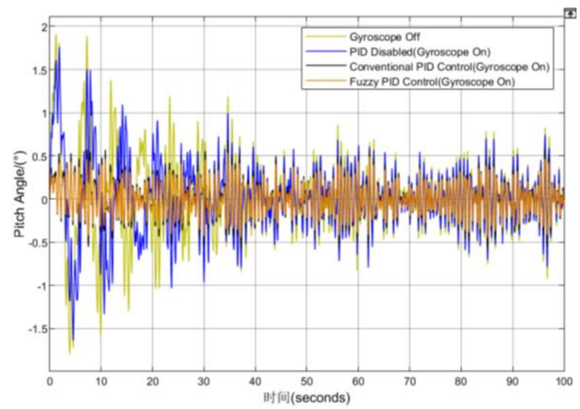


Fig.9. Stabilization Performance of the Gyroscopic Stabilizer under Different Wave Heights

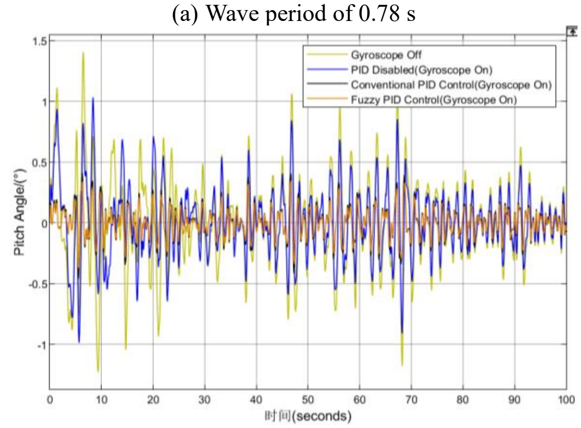
Figure 9 shows the pitch reduction ratios obtained from the MATLAB/Simulink simulations of the gyroscopic stabilizer operating under passive control, conventional PID control, and fuzzy PID control as a function of wave height. As shown in Fig. 9, under the selected simulation conditions, the pitch reduction ratio increases steadily as the wave height increases from 0.04 m to 0.20 m. Under passive control, the pitch reduction ratio reaches 22% when the wave height is 0.20 m. Under conventional PID control, the corresponding pitch reduction ratio increases to 60%, while under fuzzy PID control, it further improves to 64%. These results indicate that the gyroscopic stabilizer can provide effective pitch reduction across different wave heights. Moreover, for a given rotor speed and wave period, a larger wave height led to a higher pitch reduction ratio. Compared with conventional PID control, the fuzzy-PID-controlled gyroscopic stabilizer consistently achieved enhanced stabilization performance.

Stabilization Performance of the Gyroscopic Stabilizer under Different Wave Periods

Under a wave height of h = 6 m, wave periods of T = 5.5 s, 10 s, and 12.5 s are selected to represent low-, medium-, and high-frequency sea states in the North Sea, respectively. Based on the Froude similarity criterion, the scaled wave height and periods are h =0.12 m and T =0.78 s, 1.414 s, and 1.77 s. Figure 10 shows the time-domain responses of the platform pitch motion under different wave periods and control strategies of the gyroscopic stabilizer, with the rotor operating at the rated speed of 2000 rpm. As shown in the figure, the pitch motion exhibited the largest amplitude when the gyroscopic stabilizer was deactivated. Both conventional and fuzzy PID controls provide effective pitch reduction, with the smallest pitch amplitude achieved under the fuzzy PID control. Moreover, as the wave period increased, the effectiveness of the gyroscopic stabilizer gradually improved. The time-domain response at the wave height of T = 1.414 s is shown in Figure 6(b).



(a) Wave period of 0.78 s



(b) Wave period of 1.77 s

Fig.10. Time-Domain Responses of Floating Wind Turbine Pitch Motion under Different Wave Periods.

Figure 11 presents the pitch reduction ratios obtained from the MATLAB/Simulink simulations for the gyroscopic stabilizer operating under passive control, conventional PID control, and fuzzy PID control as a function of the wave period. As shown, under the selected simulation conditions, the pitch reduction ratio increases steadily as the wave period increases from 0.78 s to 1.77 s. Under passive control, the pitch reduction ratio reaches 23% when the wave period is 1.77 s. Under conventional PID control, the corresponding ratio increases to 65%, while under fuzzy PID control, it further improves to 69%. These results indicate that the gyroscopic stabilizer provides an effective pitch reduction across different wave periods. Moreover, for a given rotor speed and wave height, longer wave periods led to higher pitch reduction ratios. Compared with conventional PID control, the fuzzy-PID-controlled gyroscopic stabilizer consistently achieved enhanced stabilization performance.

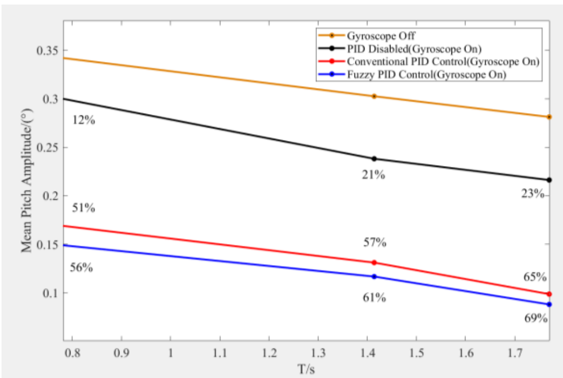


Fig.11. Stabilization performance of the gyroscopic stabilizer under different wave periods

CONCLUSIONS

This study proposes a fuzzy PID control strategy for a gyroscopic stabilizer to suppress the pitch motion of floating offshore wind turbine (FOWT) platforms. This strategy combines conventional PID control with fuzzy logic, enabling the real-time adaptive adjustment of PID parameters. Numerical simulations were conducted using the MATLAB/Simulink model of an FOWT platform equipped with a gyroscopic stabilizer. The results show that, under different rotor speeds and sea conditions, the fuzzy-PID-controlled gyroscopic stabilizer outperforms both conventional PID control and passive control in terms of pitch reduction performance. The fuzzy PID controller effectively reduced the mean pitch amplitude, and the stabilization performance of the gyroscopic stabilizer improved further as the rotor speed, wave height, or wave period increased, with the fuzzy PID control consistently achieving the best results. These findings indicate that the proposed fuzzy PID control strategy can reliably and effectively suppress the pitch motion of floating wind turbine platforms under irregular and complex sea conditions.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (52301328), to which the authors are most grateful.

REFERENCES

Hu, J., Hu, D., & Xiao, J. (2017). Research on motion control and simulation of underwater vehicle based on fuzzy theory. *Ship Science and Technology*, *39*(23), 59–63.

Ji, C., & Sun, W. (2018). Simulink and Application of Variable Universe Adaptive Fuzzy-PID Control System. *Measurement & Control Technology*, *37*(10), 119–123.

Jiang, T. (2011). *Simulation research on ship rolling motion and fin stabilizing control system*. Dalian Maritime University.

Lin, C. W., Liu, M., & Zhu, J. G. (2013). Research on fuzzy adaptive PID control algorithm based on Siemens PLCSIM. *In 3rd International Conference on Electric and Electronics*, 293–296.

LIU, Y., XIA, Z., ZHANG, J., & FAN, S. (2022). On Ship Roll Stabilization Based on Gyrostabilizer. *Ship & Boat*, *33*(04), 124.

Lu, J., & Chen, S. (2011). Active gyro-stabilizer for nonlinear roll suppression of marine vehicles. *Journal of Mechanical Engineering*, *47*(19), 86–90.

Ou, J., Long, X., Li, Q. S., & Xiao, Y.Q. (2006). Vibration control of steel jacket offshore platform structures with damping isolation systems. *Engineering Structures.*, *29*(7), 1525–1538.

Ou, J., Long, X., Li, Q., & Xiao, Y. (2007). Vibration control of steel jacket offshore platform structures with damping isolation systems. *Engineering Structures*.

Qi, Z., Sun, W., Chen, Y., & Zhao, W. (2018). Research progress on pitching and its suppression of floating offshore wind turbines. *In Proceedings of the 37th Chinese Control Conference*, 486–490.

QIE, T., ZHENG, J., & ZHANG, L. (2025). Parameter optimization of ship anti-roll gyro control systembased on genetic algorithm. *Chinese Journal of Ship Research*, *20*(3), 223–231.

Song, K. S., Kim, S. M., Kwak, M. K., & Zhu, W. (2023). Development of a control algorithm for active control of rolling motion of a ship using a gyrostabilizer. *Ocean Engineering*, *280*(114669).

Wang, J., Yang, Y., & Qian, yuheng. (2015). Design of a control moment gyroscope controller based on PID method. *Experimental Technology and Management*, *32*(04), 92–97.

Wang, L. (2021). *Research on Stability of Offshore Approach BridgePlatform Based on Anti-rolling Gyro*. Jiangsu University of Science and Technology.

Wang, S., Shi, Y., & Feng, Z. (2011). A method for controlling a loading system based on a fuzzy PID controller. *Mechanical Science and Technology for Aerospace Engineering*, *30*(1), 166–172.

Wang, Z. (2021). *Research on motion control of an underwater vehicle based on fuzzy PID*. Qingdao University of Science and Technology.

Wang, Z., & Xu, H. (2025). Temperature Control System for Agricultural Greenhouses Based on Adaptive Fuzzy PID. *Shaanxi Agricultural Science*, *71*(09), 88–93.

Yan, Y., Guo, H., Hou, J., Wang, R., & Li, G. (2024). Fuzzy PID based algorithm for Adaptive Control of a balancing vehicle. *Times Automobile*, *21*, 110–113.

Yang, X. (2024). *Research on the anti-roll performance of OC4 floating wind turbine platform based on gyrostabilizer*. Shanghai Maritime University.

Yin, H., Li, D., & Deng, X. (2022). *A novel floating wind turbine foundation with box-type heave plates (Chinese Patent No. CN114604376A)*.

YU, W., & Yang, K. (2018). Design of Cascade Fuzzy Self-Adaptive PID Control Cystem for Four-Rotor Unmanned Aerial Vehicle. *Machinery Design and Manufacture*, *1*, 227–231.

ZHANG, J., WANG, J., LI, H., & WANG, F. (2025). Research progress on pitching and its suppression of floating offshore wind turbines. *Journal of Hohai University (Natural Sciences)*, *53*(1), 103–110.

Zhu, Y. (2020). *Parameter Adaptive Optimization of Ship Antiroll GyroConsidering Random Sea Conditi*. Jiangsu University of Science and Technology.