Hydrodynamic and Static Stability Analysis of a Hybrid Offshore Wind-Wave Energy Generation: An Expansion of Semisubmersible Floating Wind Turbine Concept

Payam Aboutalebi, Aitor J. Garrido, Izaskun Garrido, Dong Trong Nguyen, and Zhen Gao

Abstract—**Marine structures like Floating Wind Turbine (FWT) is exposed to the oncoming waves and wind that can cause oscillatory motions within the system. These undesired oscillations can have negative impacts on the efficiency of the system, reduce its lifespan, hinder energy extraction, increase stress levels, and raise maintenance costs. To mitigate these negative impacts, the integration of Wave Energy Converters (WECs) into the FWT system has been proposed. This hybrid system may be capable of extracting coupled wind-wave energy and transferring electrical power to the shared grid. This paper presents an investigation of the use of Oscillating Water Columns (OWCs), a type of WECs, within a FWT system. The purpose of using an OWC is to increase the hydrodynamic damping and reduce the resonant motions of the floating wind turbines under environmental loads, including both wind and wave loads. This is because the wave energy from OWC would be very small as compared to the wind energy. However, OWCs can provide a damping source for reducing the resonant motions of the floater, especially the pitch resonant motions. This would be very beneficial for the power performance of the floating wind turbine and the structural design of the floater. The purpose of this paper is to redesign the original FWT platform to accommodate the additional OWCs by considering the hydrostatic stability and hydrodynamics since the new elements, the OWCs, can significantly change the response of the platform. The redesign of the original FWT involves the integration of OWCs within two out of three columns of an existing semisubmersible platform for a 12 MW FWT. To do this, two moonpools, which are consistent with OWC air chambers, have been created within two columns of the FWT. The water ballast was designed for the columns with and without OWCs. After that the redesign is done hydrostatic stability and hydrodynamics analyses are evaluated. The hydrodynamics properties are discussed in terms of the hybrid platform response as compared to the original platform. The hybrid platform was modeled using GeniE and the hydrostatic stability and hydrodynamics of the system was evaluated by HydroD, tools developed and marketed by DNV. The results of this study demonstrate the potential benefits of integrating OWCs within a FWT system in terms of reducing the platform oscillatory motion.**

Index Terms—**Hydrodynamic analysis, Static stability analysis, Oscillating water column, Floating wind turbine**

I. INTRODUCTION

GLOBAL warming, which is mostly caused by the usage of fossil fuels, has recently become a serious issue for the world. Rising amounts of carbon dioxide and other greenhouse gases in the atmosphere contribute to rising temperatures and altering weather patterns, both of which have far-reaching environmental, social, and economic effects. Reduced reliance on fossil fuels through the use of renewable energy sources such as solar, wind, and hydro power is one of the most effective strategies to prevent global warming. Renewable energy methods produce electricity with low or no greenhouse gas emissions, making them an important component of the answer to climate change [1]. We can assist lessen the effects of global warming while simultaneously supporting economic growth, energy security, and environmental sustainability by speeding the development and implementation of renewable energy technology.

Floating wind platforms can potentially harness both wind and wave power supplies by adding OWCs, which are one of the most investigated class of WECs. The combined system of FWT-OWCs can significantly reduce costs by taking advantage of shared operation and maintenance as well as common grid infrastructure [2]. However, a major challenge is stabilization of FWTs to alleviate undesired platform vibrations and to maximize energy output. Such vibrations can reduce aerodynamic efficiency, shorten the longevity of the tower due to fatigue, and increase stresses on various components such as blades, rotor shafts, and yaw bearings [3]. Thus, it is crucial to limit FWT platform motions within an acceptable range.

To address the challenge of stabilizing FWTs and optimizing their energy generation potential, a range

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of innovative solutions have been proposed by researchers in the field. One approach involves the use of heave plates attached to the semisubmirssible FWT, as demonstrated by the work of P. Mello et al. [4]. Other researchers, such as M. Kamarlouei et al. [5], have experimented with the installation of catenary mooring cables and WECs to reduce heave and pitch amplitude. In barge-type FWTs, inerters have been proposed as a means of controlling tower displacements, as described in studies by Y. Zhang et al. [6]. J. Sarmiento et al. [7] explored the potential of hybrid FWT-WEC systems to maximize the extraction of wind and wave energy. Through ongoing research, it is hoped that new and effective approaches will continue to emerge, paving the way for the widespread implementation of FWTs as a key source of renewable energy.

Despite these efforts, there is still a need for more research on strategies to control the valves of OWCs, especially for hybrid systems that incorporate nonlinear equations of motion, such as the square-shaped moonpool design proposed by J.M. Jonkman [8]. Similarly, the performance of hybrid barge-type FWT-OWCs needs to be further analyzed under different sea states to increase their stability, as suggested by P. Aboutalebi et al. [9]–[12].

This paper explores the possibility of the use of OWCs inside a semisubmersible FWT with redesigning a new platform for housing the OWCs. To do so, two chambers inside the columns of the FWT have been integrated. Then, hydrostatic stability and hydrodynamic analyses have been done for both the original FWT and FWT-OWCs systems.

This paper is organized as follows. Section II describes the equations of motion of FWTs. Section III explains the obtained results for hydrostatic stability and hydrodynamic analyses of the systems and finally, section IV concludes with some noteworthy findings.

II. PROBLEM STATEMENT

In this research study, a semisubmersible FWT have been modified to integrate OWCs system. The original substructure model is called INO WINDMOOR designed to support WINDMOOR 12 MW wind turbine on one of its columns [13]. As can be seen in Fig. 1, the INO WINDMOOR was initially designed as a semisubmersible wind turbine platform with a structure composed of three columns connected by pontoons and deck beams. The INO WINDMOOR platform characteristics have been detailed in Table. I.

In addition, the mooring system consists of three catenary lines that use a combination of chain and polyester materials to provide a pretension of 1050 kN and the water depth of 150 m was considered during the design process. The WINDMOOR 12 MW wind turbine charactristics are detailed in Table. II.

Upon retaining the primary characteristics of the WINDMOOR 12MW wind turbine, the substructure of the wind turbine has undergone modifications to incorporate dual OWC systems. To do so, a chamber of 4.5 m have been created inside the two columns of the substructure where the tower is not installed on, as showed in Fig. 2. The OWCs installed in the modified WINDMOOR 12MW wind turbine each consist of an air chamber connected to a turbine generator via a power take-off (PTO) system. The chamber has an opening below the waterline, allowing waves to push water inside and compress the air within. This compressed air then drives the turbine, providing torque to the generator. As the wave water retreats, the air is pulled out in the opposite direction, but the turbine continues rotating thanks to its self-rectifying design. The OWCs' valves are responsible for controlling the compression and decompression of air inside the air chambers, helping to reduce oscillations in the system. Figure 3 shows the throttle valve setup in the PTO. However, in this study, the throttle valves of the OWCs are kept open to evaluate the system's stability without any control on the OWCs.

Fig. 1. Concept of WINDMOOR 12 MW floating wind turbine [13].

TABLE I
CHARACTERISTICS OF THE REMODELED INO WINDMOOR SUBSTRUCTURE

Property	Value
Column diameter	15 m
Column height	31 m
Pontoon width	10 m
Pontoon height	4 m
Center-center distance	61 m
Deck beam width	3.5 m
Deck beam height	3.5 m
Total substructure mass including ballast	12058t
Total substructure CGx	-6.34 m
Total substructure CGy	0 m
Total substructure CGz	-10.02 m

TABLE II
PROPERTIES OF THE WINDMOOR 12 MW WIND TURBINE

Parameter	WINDMOOR 12 MW
Rated electrical power (MW)	12 MW
Specific power	324.8 W/m^2
Rotor orientation	Clockwise rotation - upwind
Number of blades	3
Rotor diameter	216.9 m
Hub diameter	5 m
Blade length	105.4 m
Blade prebend	6.8 m
Shaft tilt	6.0 deg
Rotor precone	-4.0 deg
Hub height	131.7 m
Cut-in/rated/cut-out wind speed	4.0/10.6/25.0 m/s
Generator efficiency	94.4 %
Cut-in/ rated rotor speed (rpm)	5.5/7.8
Maximum Tip Speed (m/s)	88.6
Blade mass (kg)	3×63.24
Hub mass (kg)	60000
Nacelle mass (kg)	600000

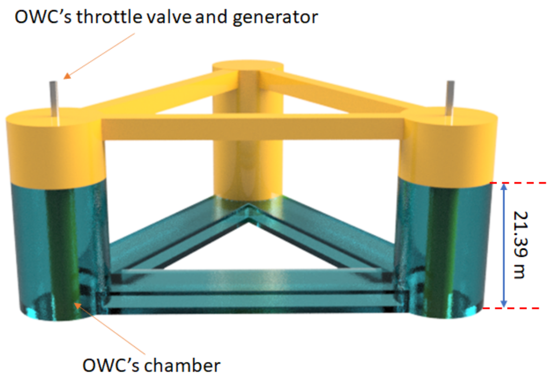

Fig. 2. The substructure for the FWT-OWCs system with ballast representation.

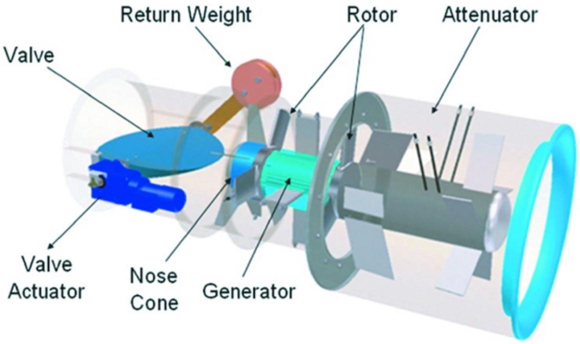

Fig. 3. Throttle valve configuration in PTO.

The coupled FWT, support platform with OWCs have the following general nonlinear time-domain equations of motion:

$$M_{ij}(x,u,t)\ddot{x}_j = f_i(x,\dot{x},u,t) \tag{1}$$

where M_{ij} defines the inertia mass elements and x describes the states of the system. u stands for control inputs. The external forces of aerodynamic loads on the blades and nacelle, hydrodynamic forces on the platform, elastic and servo forces and PTO have been described as f_i on the right hand-side of Equation 1.

The equation of motion in frequency domain can be written as:

$$I_{FWT}(\omega)\ddot{x} + B_{FWT}(\omega)\dot{x} + K_{FWT}x = \vec{f}_{FWT}(\omega) \tag{2}$$

where I_{FWT}, B_{FWT} and K_{FWT} represent the inertia elements, damping components and stiffness matrix, respectively and the linearization was already performed. $\vec{f}_{FWT}(\omega)$ denotes the hydrodynamic force and aerodynamic loads. The term x in Equation 2 expresses the platform motion by:

$$x = \begin{bmatrix} surge \\ sway \\ heave \\ roll \\ pitch \\ yaw \\ towerfore-aft \\ towerside-to-side \end{bmatrix} \tag{3}$$

The inertia elements of FWT can be defined by:

$$I_{FWT}(\omega) = A_{Hydro}(\omega) + M_{Platform} + M_{Tower} \tag{4}$$

where $M_{Platform}$ is platform mass and M_{Tower} is the tower mass including tower-top rotor-nacelle assembly. A_{Hydro} expresses the platform's added mass, can be calculated by the panel radiation program namely WADAM [14].

The stiffness matrix K_{FWT} may be expressed by:

$$K_{FWT} = K_{Hydro} + K_{Mooring} + K_{Tower} + K_{PTO} \tag{5}$$

here K_{Hydro}, $K_{Mooring}$, K_{Tower} and K_{PTO} describe the platform's hydrostatic restoring matrix, the mooring lines spring stiffness elements, the tower stiffness coefficients and PTO stiffness respectively.

The damping coefficients can be described as:

$$B_{FWT}(\omega) = B_{Hydro}(\omega) + B_{Tower} + B_{PTO} \tag{6}$$

where B_{Hydro} is platform's damping elements from the radiation problem and the drag damping, and B_{Tower} is damping matrix of the flexible tower. B_{PTO} is the PTO damping.

In order to calculate the added mass, damping coefficients, restoring matrix hydrodynamic force, a finite element model from the meshed platform has been obtained and analyzed by the WADAM tool. The considered size of each mesh is 0.75 m.

III. HYDROSTATIC STABILITY AND HYDRODYNAMIC ANALYSES

In this section, hydrostatic stability and hydrodynamic analyses have been conducted. In order to observe the hydrostatic stability analysis, the Intact criteria have been evaluated according to Norwegian Maritime Authority (NMA)- Regulations for Mobile Offshore Units (2003 Edition) - General Regulations V1-3-878/91-p20.

Intact hydrostatic stability is a crucial aspect of offshore turbine design, as it determines a FWT's ability to maintain its upright position during operating conditions. In simple terms, intact hydrostatic stability refers to the ability of an FWT to resist capsizing or heeling over due to external forces like wind and waves in

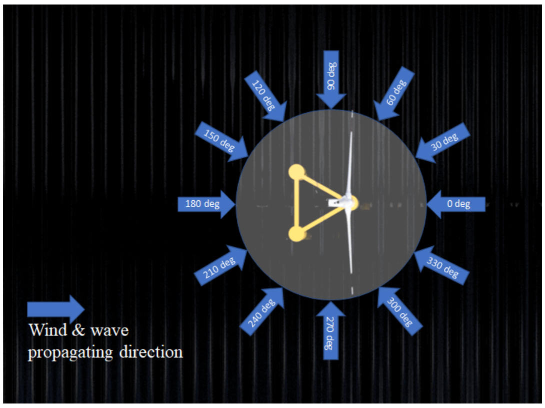

Fig. 4. Wind and wave direction.

FWTs. The wave and wind direction can be seen in Fig. 4.

Fig. 5 and Fig. 6 represent the righting moments and wind heeling moment with respect to heeling angle for the remodeled WINDMOOR 12 MW FWT and the redesigned hybrid FWT-OWCs system. The overturning moment exposed to the wind turbine have been calculated based on the maximum thrust on the blades [13]. This overturning moment is represented in the figures in dash black as wind heeling moment. Based on different heeling angle direction, the righting moments have been plotted in the figures in order to evaluate the Intact stability for both systems. Five criteria have been evaluated for the Intact static stability. The first criterion is that the equilibrium inclination angle with wind should not exceed 17 degrees.The second criterion is that the second righting/heeling moment intercept should exceed 30 degrees. The second intercept is where the wind heeling moment crosses the righting moment. Then, the righting moment curve should be positive over the entire range of angles from upright to the second intercept. Next criterion is that metacentric height in equilibrium must be greater than 1 m. The last criterion is that for column-stabilized units, the area under the righting moment curve to the angle of downflooding should be not less than 30% in excess of the area under the wind heeling moment curve to the same limiting angle.

The aforementioned criteria have been fulfilled for both the WINDMOOOR 12 MW FWT and the hybrid FWT-OWCs after evaluating in a tool called Hydro developed by DNV [15].

Once the static stability of the system is guaranteed, the hydrodynamics of the system can be evaluated based on RAO to observe the behavior of the system. The RAO is typically expressed as a function of the frequency of the input, and can be calculated through theoretical analysis, numerical simulations, or physical testing. The RAO is an important parameter in the design and analysis of offshore structures, as it provides a means of predicting the response of the structure to various input conditions. Hence, through WADAM analysis, the transfer functions for different states of the systems have been obtained.

The RAOs for surge in Fig.7, sway in Fig. 8, heave in Fig. 9, roll in Fig 10, pitch in Fig. 11 and yaw in Fig. 12 are shown. The blue and red curves represent the RAOs for WINDMOOR FWT and the hybrid FWT-OWCs system respectively. In addition, the wave direction for all the RAOs have been considered as the heading wave of zero degrees. The surge RAO in Fig.7 increases as the wave periods become longer and a small difference can be seen for the WINDMOOR FWT and FWT-OWCs system in surge motion. Hence, the same behaviour is expected for both systems. The sway RAO in Fig. 8, roll RAO in Fig. 10 and yaw RAO in Fig. 12 show small amount of amplitude for both systems. Although the RAO in roll has worsened with the new hybrid system, the improved control system, or the design modification, can solve the problem. This means that these modes are not provoked because of the imposed wave direction. For heave RAO in Fig. 9, as the wave period gets longer the heave amplitude becomes higher until it gets to its natural frequency. After that, the heave RAO becomes lower to get to 1 m/m. It is noticeable that the heave RAO for the FWT-OWCs is lower than that of for the WINDMOOR FWT. It shows a positive impact of the novel design in oscillation reduction in heave natural frequency.

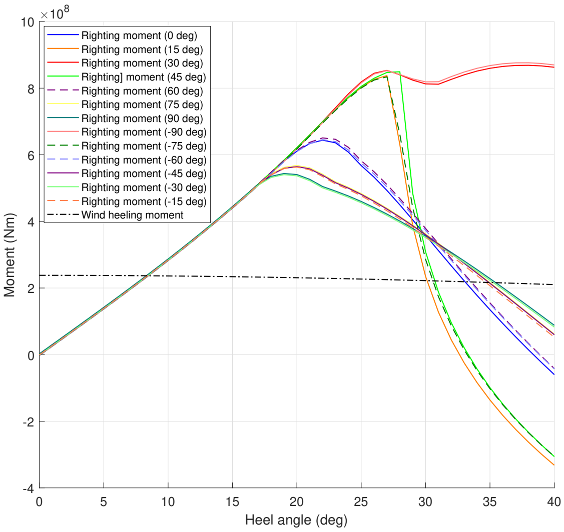

Fig. 5. Moments for the remodeled WINDMOOR FWT without OWCs.

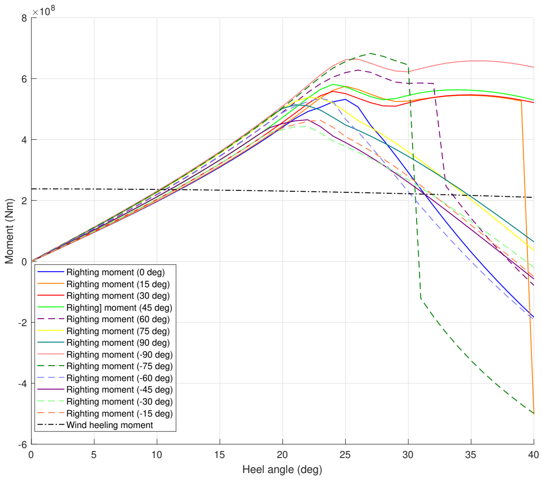

Fig. 6. Moments for the hybrid FWT-OWCs.

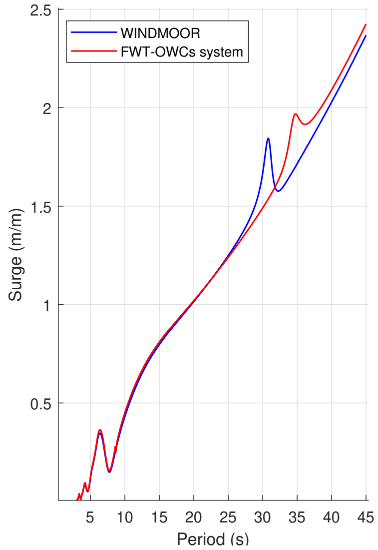

Fig. 7. Surge RAO at the wave direction of 0 deg.

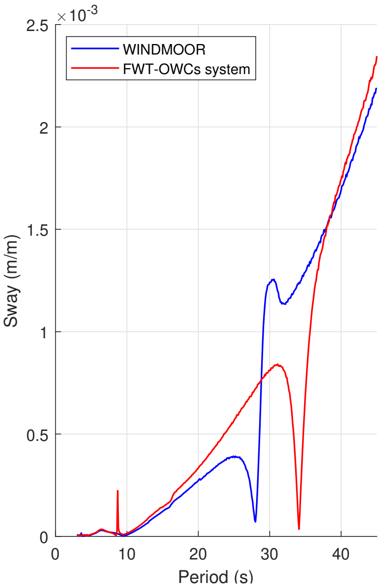

Fig. 8. Sway RAO at the wave direction of 0 deg.

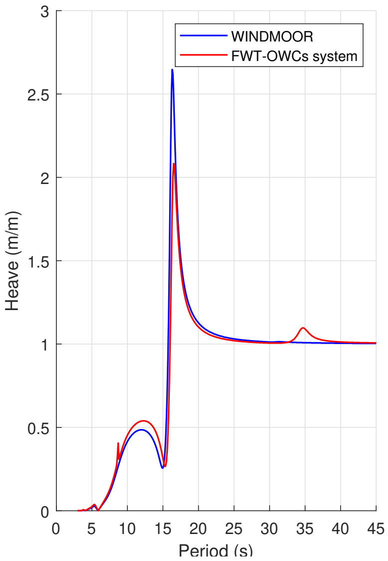

Fig. 9. Heave RAO at the wave direction of 0 deg.

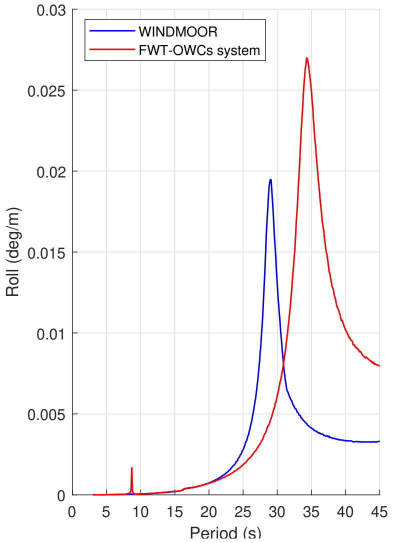

Fig. 10. Roll RAO at the wave direction of 0 deg.

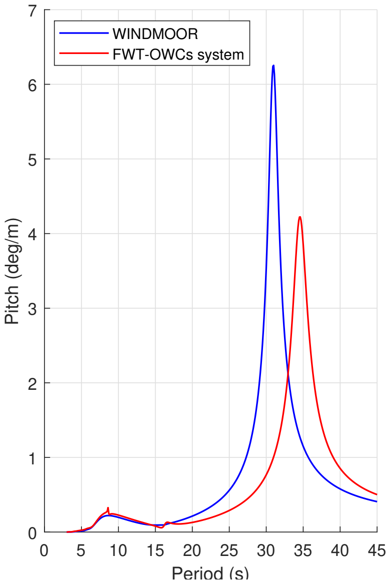

Fig. 11. Pitch RAO at the wave direction of 0 deg.

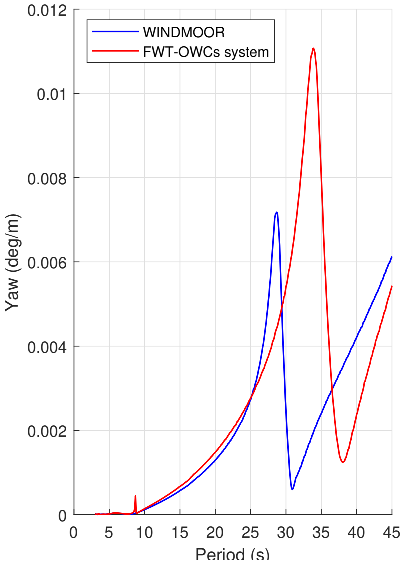

Fig. 12. Yaw RAO at the wave direction of 0 deg.

The most important mode in this study is pitch as it has a significant impact on energy extraction. As can be seen in Fig. 11, the pitch RAO becomes longer with the increase of the wave period until the natural frequency. After that, it gets lower to get to around zero for both systems. The point in the figure is that the natural frequency is shifted forward for the hybrid FWT-OWCs system compared with the WINDMOOR FWT. This shift is because of the change in mass distribution, or the change of GMT/GML. Besides, the amplitude of the pitch decreased significantly for the FWT-OWCs system compared to the WINDMOOR FWT, showing the positive effect of the OWCs in oscillation damping in the FWTs.

IV. Conclusion

This paper investigates the possibility of the integration of OWCs inside a semisubmersible FWT. The equations of motion in frequency domain for the FWTs were described and hydrostatic stability and hydrodynamic analyses were evaluated. To do so, a comparison study was conducted between the original WINDMOOR FWT and the proposed hybrid FWT-OWCs.

It was showed that the Intact stability criteria were fulfilled for both systems exposed to maximum wind thrust. In hydrodynamic analysis for the wave heading of zero degrees, it was illustrated that the RAOs at natural frequencies for pitch and heave decreased significantly, showing the positive impact of the OWCs in FWTs. Furthermore, the paper presents the possible integration of the OWCs in semisubmersible FWTs.

Future work may include a controller for the airflow control using a valve in the OWC in order to implement an active control system for the hybrid FWT-OWCs. In addition, in the next steps, the system will be evaluated under more realistic conditions, taking into account the effect of irregular waves and wind. To achieve this, time domain simulations will be conducted to assess the performance of the controller in improving the hybrid system's response and stability.

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