Dual Airflow Control Strategy for Floating Offshore Wind Turbine Stabilization using Oscillating Water Columns

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Abstract. The stability of Floating Offshore Wind Turbine (FOWT) has been the focus of many researchers in the last years. Many concepts proposed the use of passive structural control such as inerter and Tuned Mass Dampers (TMD). This paper presents a new concept combining a barge-based FOWT with Oscillating Water Columns (OWC) to help reduce the undesired vibrations induced from waves and wind. In this work, an airflow control strategy developed for the OWCs integrated in the barge platform of a FOWT. The control strategy has been designed to lessen the pitching of the platform and the displacements of tower fore-aft with the intention of stabilizing the floating platform. This objective is achieved by controlling the air valves located at the top of the OWCs' capture chambers. The comparative study between the FOWT with standard barge and the proposed FOWT with OWC-based barge, based on the analysis of the free decay responses, displays an enhancement in the stability of the platform.

Keywords: Airflow Control, Air Valve, ITI Energy Barge Platform, Floating Offshore Wind Turbine, Oscillating Water Column, Structural Control.

1 Introduction

The global wind power progress has been gradually and steadily transforming from onshore to offshore. In the past, onshore and nearshore wind turbines were disliked for their noise and visual pollution [1], big foundation, complex structures, and costly expenses [2]. On the contrary, offshore wind farms have no space-restrictions, stronger and steadier wind resources making them more advantageous and exploitable. Loads produced by winds and waves on the FOWT structure raise the platform's stress, damages, failures, and maintenance cost while reducing its efficacy and lifecycle.

With the global wind power transformation to offshore technologies, researchers and investors promoted the use of multipurpose platforms. Many multipurpose concepts proposed the combination of energy resources extraction. Among these concepts, the most studied and exploited is the wind-wave platform that combines Wind Turbines (WT) and wave energy converters to collect both the power of waves and winds [3–5].

Previous investigations studied the use of OWCs with a FOWT and the outcome showed promising results. In [6] a WEC array has been paired with a spar-based FOWT from National Renewable Energy Laboratory (NREL) known as OC3-Hywind FOWT. And in [7] both external and internal heave WECs have been investigated on OC3-Hywind by A. Slocum et *al.* Also, in [8] M. Kamarlouei et *al.* have drawn the conclusion that the platform vibrations in heave and pitch is reduced when installing a WEC array. Still, the presented concepts haven't employed OWCs in barge platforms.

This paper's objective is to combine a FOWT with an OWC to extract wave and wind energy. Moreover, the paper studies the stabilization of the FOWT with the use of OWCs to lessen the unwanted vibrations of the structure. The FOWT understudy is the NREL 5MWwind turbine fixed on top of an ITI Energy barge platform [9]. The OWCs will be governed by a dual airflow control to adequately open and close the air valves, regulating the airflow and pressure within each air chamber [10–12].

The rest of the paper has been arranged as: Section 2 explains the method used to develop the dynamic OWC-based FOWT model, the added OWCs forces and the designed dual airflow control. Section 3 details the simulation results achieved of the new structure and a comparative study analyzing its structural behavior with standard FOWT. Lastly, Section 4 terminates the manuscript with some concluding remarks.

2 Materials and Methods

The investigation introduced in this manuscript introduces a new stabilization concept for the FOWT shown in Fig. 1. The studied FOWT is the 5MW NREL offshore baseline WT attached on top of an ITI Energy barge commonly used to analyze load interactions and verify new conceptions of FOWTs. The most significant features of the 5MW wind turbine and the ITI Energy barge structure have been summarized in Table 1 and more specific details on the system can be found in [13] by J. Jonkman et *al.*.

Unlike the onshore WTs, which only suffer from fore-aft and side-to-side displacements because of the bending moment imposed on the tower, FOWTs suffer from tower top displacement, rotational modes, and translational modes, increasing the vibration and the instability of the structure.

In accordance with previous investigations, it has been established that the variation of the platform pitch angle adds the most to the tower bending [14, 15]. Moreover, because the tower bending created by the pitching of the barge affects the tower top displacements thus the fore-aft mode is significant as well in the FOWT's stability. In this sense, the FOWT model focuses on these two modes, namely the platform pitch angle and the tower's first fore-aft bending mode. In addition, the study presented in the present manuscript focusses on the vibration dynamics of the floating offshore wind turbine associated with the interaction of the waves. Accordingly, the impact of the winds on the turbine has been disabled to attain a linear dynamic mathematical model and develop the suitable active structural control strategy for platform stabilization.

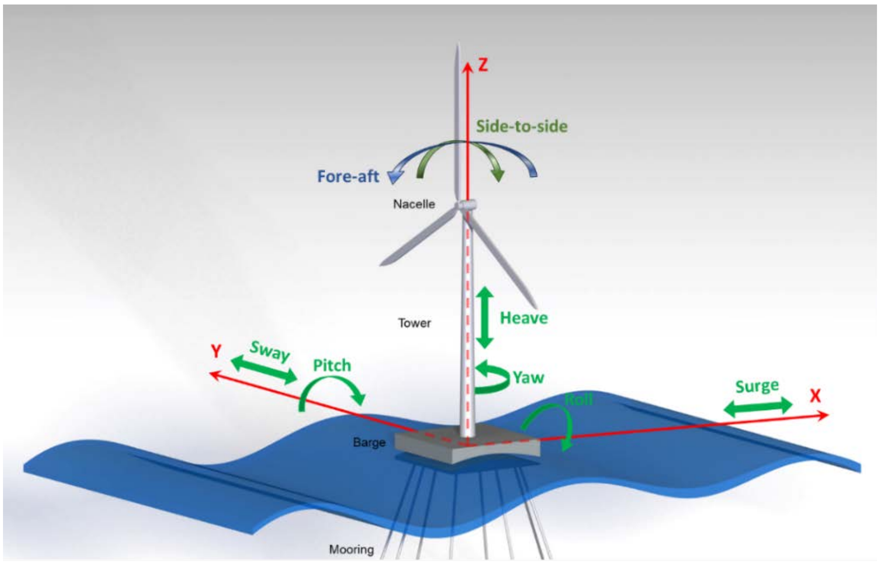

Fig. 1. Schematic of the considered floating offshore wind turbine.

Table 1. Features of the studied floating offshore wind turbine system.

NREL 5 MW Wind Turbine		**ITI Energy barge**	
Feature	Value	Feature	Value
Rated power	5MW	Platform size	40 m x 40 m x 40 m
Baseline control	Variable speed, collective pitch	Platform mass	5,452,000 kg
Tower mass	347, 460 kg	Anchor depth	150 m
Rotor diameter	126 m	Nº mooring lines	8
Hub height	90 m	Line diameter	0.0809 m
		Line mass density	130.4 kg/m

2.1 OWC-based FOWT Dynamic Model

As previously explained the DOFs with distressing the stability of the FOWT's platform the most are the platform pitch angle and the tower fore-aft displacement. Therefore, the developed model in this study will focus and describe these two DOFs to design a dynamic reduced-order mathematical model as shown in the scheme of Fig. 2 which has been adopted from [16,17].

The WT tower is presumed to be attached to the platform using a rotational spring, as a stiffness k_t, and a damper as the damping d_t. The spring constant k_p represents the stiffness of the mooring lines, hydrostatic restoring moments, and the hydrodynamic damping properties interacting with the barge platform. The viscous properties and the radiation of the waves, are represented with the damping coefficient d_p. The structural proporties of the studied FOWT are summarized in Table 2.

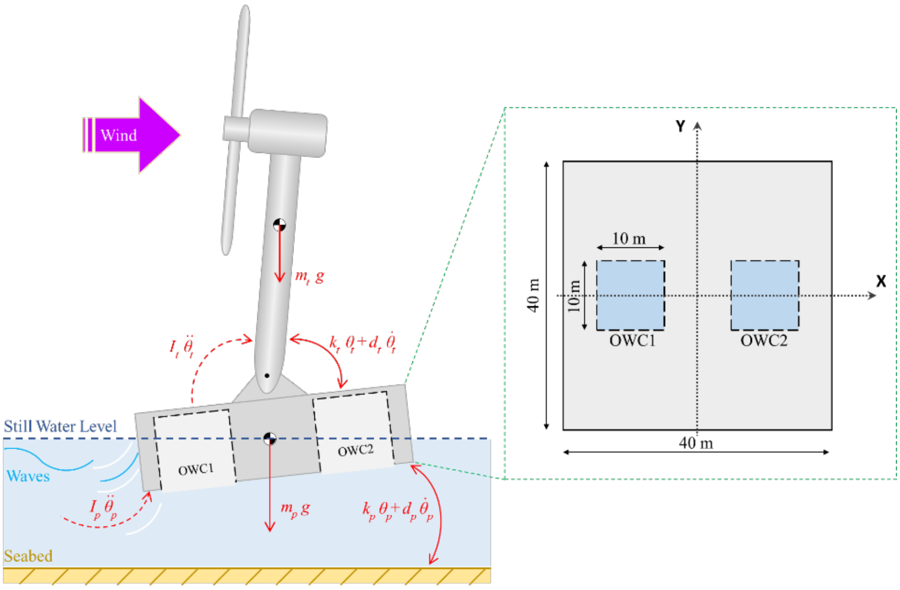

Fig. 2. Scheme of the proposed reduced-order hybrid OWC-based FOWT.

Table 2. Structural features of the studied FOWT system.

Tower		**ITI Energy barge platform**	
Feature	Value	Feature	Value
Stiffness	k_t = 9.7990 10^9 (N m rad^{-1})	Stiffness	k_p = 1.4171 10^9 (N m rad^{-1})
Damping	d_t = 2.1032 10^7 (N m s rad^{-1})	Damping	d_p = 3.6374 10^7 (N m s rad^{-1})
Inertia	I_t = 1.8217 10^9 (kg m^2)	Inertia	I_p = 1.6945 10^9 (kg m^2)

The proposed structure of the hybrid wind-wave platform is aimed to lessen the platform pitch angle and the tower fore-aft displacement. Hence, two OWCs were incorporated in the barge platform of in the front and in the back of the wind tower.

Equations (1) and (2) describe a non-conservative system possessing n generalized coordinates using the Euler-Lagrange principle:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i \qquad \left(i = 1, 2, \cdots, n\right) \tag{1}$$

$$L = T - V \tag{2}$$

with T and V are the system's total kinetic and potential energies. L represents the Lagrange operator. Q_i represent the generalized non-potential forces.

The total kinetic and potential energies may be expressed as:

$$T = \frac{1}{2} I_t \dot{\theta}_t^2 + \frac{1}{2} I_p \dot{\theta}_p^2 \tag{3}$$

$$V = \frac{1}{2} k_t \left(\theta_t - \theta_p\right)^2 + \frac{1}{2} k_p \theta_p^2 + m_t g R_t \cos\theta_t - m_p g R_p \cos\theta_p \tag{4}$$

where θ is the rotation angle, k is the spring stiffness, d is the damping coefficient, m stands for the mass, I stands for the moment of inertia about the mass center, and R stands for the distance between the center of mass and the tower hinge connecting it to the platform. The subscripts p and t refer to the platform and the tower, respectively.

The generalized non-potential forces including the wind- and wave-induced loads may be defined by:

$$\begin{cases} Q_{\theta_t} = -d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) + M_{wind} \\ Q_{\theta_p} = -d_p\dot{\theta}_p + d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) + M_{wave} - R_{owc1} f_{owc1} + R_{owc2} f_{owc2} \end{cases} \tag{5}$$

where M_{wind} and M_{wave} are the wind and wave load-induced bending moments. f_{owc1} and f_{owc2} are the forces created due to increasing pressure in the OWCs' capture chambers.

Since the platform pitch in floating platforms, do not exceed 10 degrees with the roughest winds and waves, small angles were used in the plant model. Also, presuming that the OWCs are equidistant from the tower hinge ($R_{OWC1} = R_{OWC2} = R_{OWC}$). Thus, by replacing (3)-(5) into (1) and (2) the dynamic model can be described as:

$$\begin{cases} I_p\ddot{\theta}_p - k_t\left(\theta_t - \theta_p\right) + k_p\theta_p + m_p g R_p\theta_p = -d_p\dot{\theta}_p + d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) + M_{wave} - R_{owc}(f_{owc1} - f_{owc2}) \\ I_t\ddot{\theta}_t + k_t\left(\theta_t - \theta_p\right) - m_t g R_t\theta_t = -d_t\left(\dot{\theta}_t - \dot{\theta}_p\right) + M_{wind} \end{cases} \tag{6}$$

The interaction of the FOWT with wind and waves is a complex aero-elastic and hydro-elastic process. Additionally, waves- and winds-induced structural responses possess inherent coupling [18]. The wind- and wave-induced loads M_{wind} and M_{wave} were assumed to be obtained linearly as a function of wind speed $V_{wind}(t)$ at the hub height and wave elevation $Z(t)$ to obtain a dynamic linear mathematical model of the FOWT plant. Therefore, M_{wind} and M_{wave} are modeled as first-order dynamics [18]:

$$\dot{M}_{wind}(t) = -\alpha_{wind}M_{wind}(t) + \beta_{wind}V_{wind}(t) \tag{7}$$

$$\dot{M}_{wave}(t) = -\alpha_{wave}M_{wave}(t) + \beta_{wave}Z(t) \tag{8}$$

2.2 OWCs' Forces Mathematical Model

Assuming the internal free surface of the water within the capture chamber oscillates vertically resembling a piston and assuming the pressure is uniform. Therefore the force created from the built-up pressure in the OWC chamber maybe defined as [19,20]:

$$f_{OWCi} = -p_i(t)\, S \qquad (i = 1, 2) \tag{9}$$

with $p_i(t)$ and S are the pressure and the water surface, i refers to OWC1 or OWC2.

Assuming the air in the chamber is an ideal gas, the process is adiabatic and the transformation is sufficiently slow to be reversible, thus the transformation can be regarded as isentropic and the density of the air can be described by:

$$\rho_i(t) = \rho_a\left(\frac{p_i(t)}{p_a}\right)^{\frac{1}{\gamma}} \qquad (i = 1, 2) \tag{10}$$

with p_a stands for the atmospheric pressure, ρ_a stands for the air density, and γ stands for the specific heat ratio of the air.

The linearization of the isentropic transformation yields the following form of the air density and its derivative:

$$\rho_i(t) = \rho_a \left(\frac{p_i(t)}{p_a \gamma} \right) \qquad (i = 1, 2) \tag{11}$$

$$\dot{\rho}_i(t) = \frac{\rho_a}{p_a \gamma} \dot{p}_i(t) \qquad (i = 1, 2) \tag{12}$$

The mass flow rate within the capture chambers of the OWCs may be written as:

$$\dot{m}_i(t) = \frac{d}{dt}\left(\rho_i(t)\, V_{OWCi}(t) \right) = \frac{\rho_a V_0}{p_a \gamma} \dot{p}_i(t) + \rho_a\, \dot{V}_{OWCi}(t) \qquad (i = 1, 2) \tag{13}$$

where V_0 and $V_{OWC}(t)$ are the chamber's undisturbed and instantaneous air volumes.

The volume $V_{OWC}(t)$ relies on the chamber's geometry and can be described as [21]:

$$V_{OWCi}(t) = V_0 - S\, Z_i(t) \tag{14}$$

with Z_i and S are the vertical displacement of the inner water and its surface ($S=l_c w_c$).

Therefore, the pressure rely on the air volume and the mass flow rate [21]:

$$\dot{p}_i(t) = \frac{p_a \gamma}{\rho_a V_0} \dot{m}_i(t) - \frac{p_a \gamma}{V_0} \dot{V}_i(t) \qquad (i = 1, 2) \tag{15}$$

Finally, the main features of the considered OWCs are summarized in Table 3.

Table 3. Properties of the incorporated OWC in the barge platform.

Capture Chamber		**Wells Turbine**	
Feature	Value	Feature	Value
Chamber's inner width	w_c = 10 m	Blade number	n = 5
Chamber's inner length	l_c = 10 m	Blade span	b = 0.21m
Chamber's inner height	h_c = 10 m	Blade chord length	l = 0.165m
Water density	ρ_w=1029 kg/m^3	Turbine mean radius	r = 0.375m
Atmospheric density	ρ_a=1.19 kg/m^3	Cross-sectional area	a = 0.4417 m^2
Atmospheric pressure	p_a= 101.325 kPa		

2.3 Dual Airflow Control Strategy

The dual airflow control aims to, adequately, open and close the air valves installed at the top of the capture cambers. This control will adjust the pressure in the chambers to create the forces required to alleviate the loads prompted by the winds on the tower and the waves on the barge platform [21]. The opening and closing of the valves is decided based on the pitch angle of the platform as described in Fig. 3.

If the platform is slanting to the front, the forces created by the increasing pressure inside the air chamber of OWC1 should be superior to the forces of OWC2. However, if the barge platform is slanting to the back, the forces created by the decreasing pressure inside the air chamber of OWC1 should be inferior to the forces created by the increasing pressure inside the air chamber of OWC2. In this sense, if the platform pitch angle is positive, the valve control in the chamber of OWC1 should be active in order to shut the valve and trapping the air, which will increase the pressure, while the valve control in the chamber of OWC2 should open the valve and releasing some air which will decrease the pressure. Contrariwise, if the platform pitch angle is negative, the valve control in the chamber of OWC1 should be inactive in order to open the valve and release air, which will decrease pressure, while the control in the OWC2's chamber should be active to shut the valve and trapping air, which will increase the pressure.

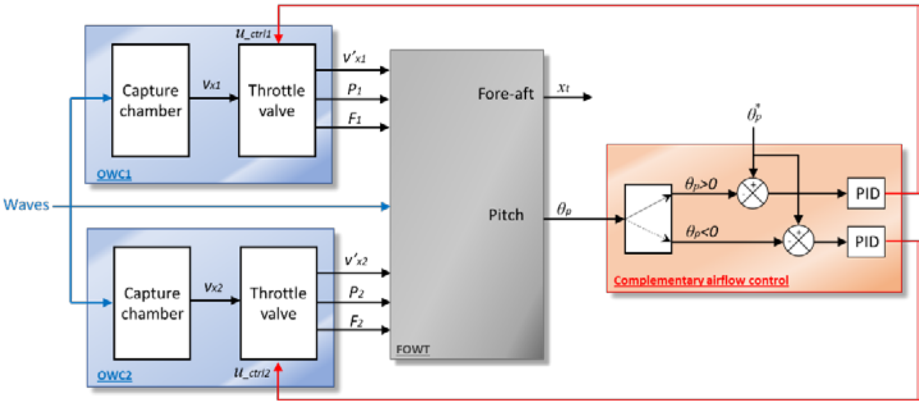

Fig. 3. Proposed dual airflow-based structural control for FOWT stability.

The developed control approach employs two PID controllers for the opening and closing of the valve plates depending on the platform pitch as illustrated in Fig. 3. Therefore, the platform pitch error is used as the input of the PID controllers and the outputs of both controllers are the control signals of both air valves.

3 Results and Discussion

For this study, the floating offshore wind turbine with a standard barge platform has been compared to a floating offshore wind turbine with the suggested OWC-based barge. In this sense, the Free Decay Response (FDR) of both structures has been analyzed and compared in order to understand their responses and the way the perturbations are tuned down in the absence of external forces or environmental excitations. Therefore, the simulation should be carried out in the absence of the aerodynamic loading from winds on the rotor and the hydrodynamic loading from waves on the barge. Thus, the wind speed $V_{wind}(t)$ at hub height and the wave elevation $Z(t)$ have been disabled during the simulations for the free decay response study.

To observe the free decay response, an initial perturbation has been introduced to the implemented OWC-based barge FOWT model as an initial pitch angle of 5 degrees of the tilted barge platform. The simulation results are illustrated in Fig.4 and Fig.5.

The FDR of the platform pitch DOF of the FOWT using the standard barge platform and the FOWT using the OWC-based barge platform are illustrated in Fig. 4. It may be observed that both pitch angles commence from 5 degrees, which is the starting value of the introduced perturbations to the FOWT platforms. According to the obtained free decay responses, the platform pitch angle was tuned down. However, in the novel FOWT using the OWC-based barge platform the pitch angle was damped out more compared to the FOWT using the standard barge platform.

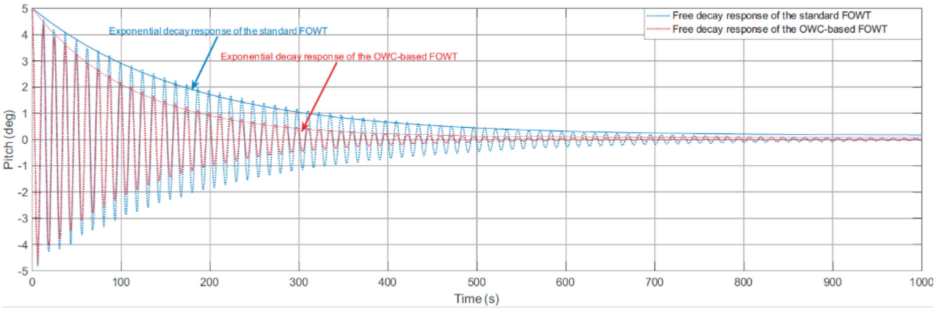

Fig. 4. FDR of the platform pitch angle in the standard and OWC-based FOWTs structures.

The free decay responses of the top tower fore-aft bending mode of the floating offshore wind turbine using the standard barge platform and the FOWT using the OWC-based barge platform are illustrated in Fig. 5. It may be observed that both pitch angles commence from the same initial value but decreases during the simulation. However, in the novel FOWT using the OWC-based barge platform the pitch angle was damped out more compared to the FOWT using the standard barge platform.

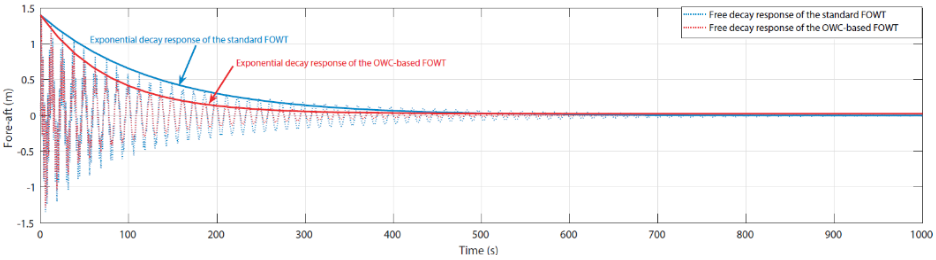

Fig. 5. FDR of the fore-aft bending in the standard and OWC-based FOWTs structures.

Based on the exponential decay technique, the damping ratio of the platform pitch angle DOF is around 1.84% in the FOWT using an OWC-based barge platform while it is around 1.66% in the FOWT using a standard barge platform. In addition, the damping ratio of the fore-aft DOF is around 1.27% in the FOWT using an OWC-based barge platform, while it is around 0.86% in the FOWT using a standard barge platform. Also, the achieved contribution-time of the proposed dual airflow control regarding the platform pitch angle's settling time is of 45.07 s.

4 Conclusions

The work introduced in this article presents a new concept of an active structural control incorporating OWCs into an ITI Energy barge platform of a FOWT. This new concept relies on the counterforces created due to the built-up pressures trapped inside the air chamber of the oscillating water columns. The produced counterforces inside the OWCs will oppose to the hydrodynamic loads imposed on the floating structure to reduce the unwanted oscillations in the platform pitch angle and tower fore-aft displacement with the intention of further stabilizing the entire structure.

A dynamic reduced order model of the proposed wind-wave hybrid FOWT concept has been developed targeting the platform pitch angle and the tower fore-aft bending. Using this mathematical model, the pressure and counterforces of the OWCs were included in order to study the impact of the use of the OWCs in opposing the hydrodynamic loads acting on the platform. The OWCs are governed by a dual airflow control, which measures the platform pitch. The platform pitch error is used as input to the implemented PID controllers. The outputs of the designed PID controllers are used as the valves' control signals. Therefore, the PID controllers will adequately adjust the pressure inside the chambers to tune down the platform pitch angle and tower fore-aft.

The results of the free decay response revealed that, compared to the FOWT structure using the standard barge platform, the platform pitch angle and the tower fore-aft of the proposed FOWT using the OWC-based barge platform were significantly damped out. Furthermore, the use of the exponential decay technique demonstrate that the damping ratios of the platform pitch angle and tower fore-aft bending mode are improved in the suggested FOWT structure using an OWC-based barge platform.

Acknowledgment

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