

Comparative Assessment of Negative Stiffness Mechanisms for Vibration Control of Floating Wind Turbine Structures

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ABSTRACT

In this research work, the vibration mitigation of floating offshore wind turbine structures is investigated through the application of vibration control systems (VCS) incorporating negative stiffness (NS) mechanisms. Conventional mass-related VCS, such as tuned mass dampers (TMDs), often require substantial auxiliary masses to achieve effective damping, which may introduce practical limitations. By contrast, the integration of NS elements offers an alternative approach capable of enhancing vibration absorption efficiency while reducing mass requirements. This is achieved by increasing the effective inertia of the auxiliary mass through the force of the NS element, rather than by increasing the mass itself. In this study, the NS mechanism is realized through a pre-stressed spring configuration, and two vibration control systems, namely the KDamper and the extended KDamper (EKD), are optimally designed. Their performance is assessed through numerical simulations that capture the nonlinear dynamic response of the controlled system. An optimization methodology is employed to identify efficient and robust designs within engineering and manufacturing constraints, and the optimized configurations are subsequently compared with a conventional tuned mass damper comprising an auxiliary mass fifty times higher. The results demonstrate that NS-based VCS provide improved damping, leading to significant reductions in structural vibrations while maintaining structural stiffness and introducing minimal additional mass. These findings underline the potential of NS mechanisms as effective alternatives to conventional vibration control strategies, thereby contributing to the increased reliability and lifetime of floating offshore wind turbine structures.

Keywords: Floating Wind Turbine, Vibration Control, Negative Stiffness, Damping

1. INTRODUCTION

Offshore wind energy has emerged as one of the most promising pillars of the global transition towards sustainable power generation, driven by the availability of high-quality wind resources and the proximity of offshore sites to densely populated coastal regions. In recent years, offshore wind turbines have undergone a rapid increase in size and rated capacity, resulting in taller towers, larger rotor-nacelle assemblies, and increasingly slender structural components. This upscaling trend, while beneficial for energy yield, has also intensified the dynamic demands imposed on offshore wind turbine structures. Floating offshore wind turbines, in particular, operate in deep-water environments where complex wind-wave interactions, platform motions, and structural flexibility lead to pronounced dynamic responses. These responses may manifest as excessive vibrations, amplified internal forces, and fatigue accumulation in critical

components of the tower and support structure (Chou & Tu, 2011). Given that structural and foundation-related costs constitute a substantial portion of the total lifecycle cost of offshore wind turbines, mitigating adverse dynamic effects is essential for improving structural reliability, extending service life, and ensuring the economic viability of offshore wind energy systems. Consequently, vibration mitigation has become a key research focus in the design and operation of modern offshore wind turbines.

Among the various approaches proposed for mitigating wind- and wave-induced vibrations, passive vibration control systems (VCS) have attracted significant attention due to their simplicity, reliability, and ease of implementation. The tuned mass damper (TMD) remains the most widely investigated passive solution, owing to its well-established theoretical foundation and successful applications in civil and mechanical engineering (Murtagh et al, 2007). In the context of wind turbines, TMDs are typically installed at the top of the tower or within the nacelle, where the amplitude of the dominant vibration modes is largest (Lackner & Rotea, 2010; Stewart & Lackner, 2014). Numerous studies have demonstrated that TMDs can effectively reduce tower displacements. However, the performance of TMDs is inherently linked to the magnitude of the auxiliary mass, often requiring relatively large mass ratios to achieve substantial damping. This requirement is particularly undesirable for offshore wind turbines, as additional mass at the upper part of the structure increases axial forces and second-order effects. To address these limitations, several alternative mass-related vibration control concepts have been proposed, including tuned liquid column dampers, pendulum-type absorbers, inerter-based systems, and hybrid configurations (Mensah & Duenas-Osorio, 2014; Chen et al, 2015). While these systems can improve certain aspects of vibration mitigation or reduce sensitivity to tuning, they generally remain constrained by similar mass-related or space-related limitations and may introduce additional complexity in design and installation.

In an effort to overcome the fundamental drawbacks associated with conventional mass-based vibration absorbers, the KDamper concept has been introduced as an advanced passive vibration control strategy (Antoniadis et al, 2016). The KDamper extends the classical TMD by incorporating a negative stiffness (NS) element in conjunction with a positive stiffness and an auxiliary mass. The key principle underlying this concept is that the force generated by the NS element acts in phase with the inertia force of the oscillating mass, effectively amplifying it without increasing the actual mass (Kapasakalis et al, 2020). As a result, the KDamper can achieve substantially higher effective damping compared to a TMD with the same auxiliary mass, or equivalently, comparable vibration mitigation with significantly reduced mass requirements. Despite the presence of NS, the KDamper is designed to remain both statically and dynamically stable through appropriate parameter selection and mechanical realization (Kapasakalis et al, 2021). Previous studies have demonstrated that KDamper-based configurations can significantly outperform conventional TMDs in reducing wind turbine tower vibrations (Kampitsis et al, 2022), while simultaneously exhibiting enhanced robustness against parameter detuning (Kapasakalis et al, 2024). Extended variants of the KDamper have further improved its adaptability to complex structural systems by offering greater flexibility in stiffness distribution and force transmission paths. These characteristics render the KDamper particularly well suited for offshore wind turbine applications, where stringent mass limitations, strong dynamic coupling, and nonlinear response characteristics demand highly efficient and reliable vibration mitigation solutions.

In this context, the present study investigates the application of negative stiffness-based vibration control systems for the mitigation of structural vibrations in floating offshore wind turbine structures. A large-scale floating offshore wind turbine is adopted as a benchmark system, and its fore-aft dynamic response under combined wind and wave excitations is examined. Two negative stiffness-based vibration control configurations, namely the KDamper and the extended KDamper (EKD), are optimally designed using a unified numerical optimization framework and compared against a conventional tuned mass damper employed as a benchmark solution. The optimization process focuses on minimizing critical structural response quantities associated with governing structural design limit states, namely the bending moments and shear forces developed along the wind turbine tower. The effectiveness of the proposed vibration control systems is assessed through nonlinear time-domain simulations, and their performance is evaluated in terms of both peak and time-dependent response characteristics. Particular emphasis is placed on highlighting the mass efficiency of negative stiffness-based systems and their suitability as lightweight alternatives to conventional mass-based absorbers for floating offshore wind turbine applications.

2. PROPOSED VIBRATION ABSORBERS AND FOWT MATHEMATICAL MODELING

2.1 Benchmark floating offshore wind turbine

A large-scale floating offshore wind turbine (FOWT) is adopted in this research work as the benchmark structural system for assessing the effectiveness of vibration control systems incorporating negative stiffness (NS) mechanisms. The reference configuration is based on the publicly available IEA 15-MW offshore reference wind turbine (Allen et al, 2020), supported by the UMaine VoltturnUS-S semisubmersible platform (Allen et al, 2020). This benchmark has been widely employed in recent offshore wind research and is representative of next-generation deep-water offshore wind technology (Chai et al, 2024). Its large rotor-nacelle assembly, slender tower, and low inherent structural damping render it particularly suitable for investigating advanced vibration mitigation strategies.

The reference FOWT consists of a three-bladed horizontal-axis wind turbine mounted on a floating steel tower, which is supported by a four-column semisubmersible platform anchored to the seabed through a spread catenary mooring system. The turbine has a rated power of 15 MW and places the rotor-nacelle assembly (RNA) at a hub height of 150 m above the still water line (SWL). The platform operates in deep water conditions, where conventional fixed foundations are not feasible, and provides global stability through buoyancy and mooring stiffness. A schematic representation of the overall system configuration, including the tower, floating platform, and reference coordinate system, is shown in Figure 1(a).

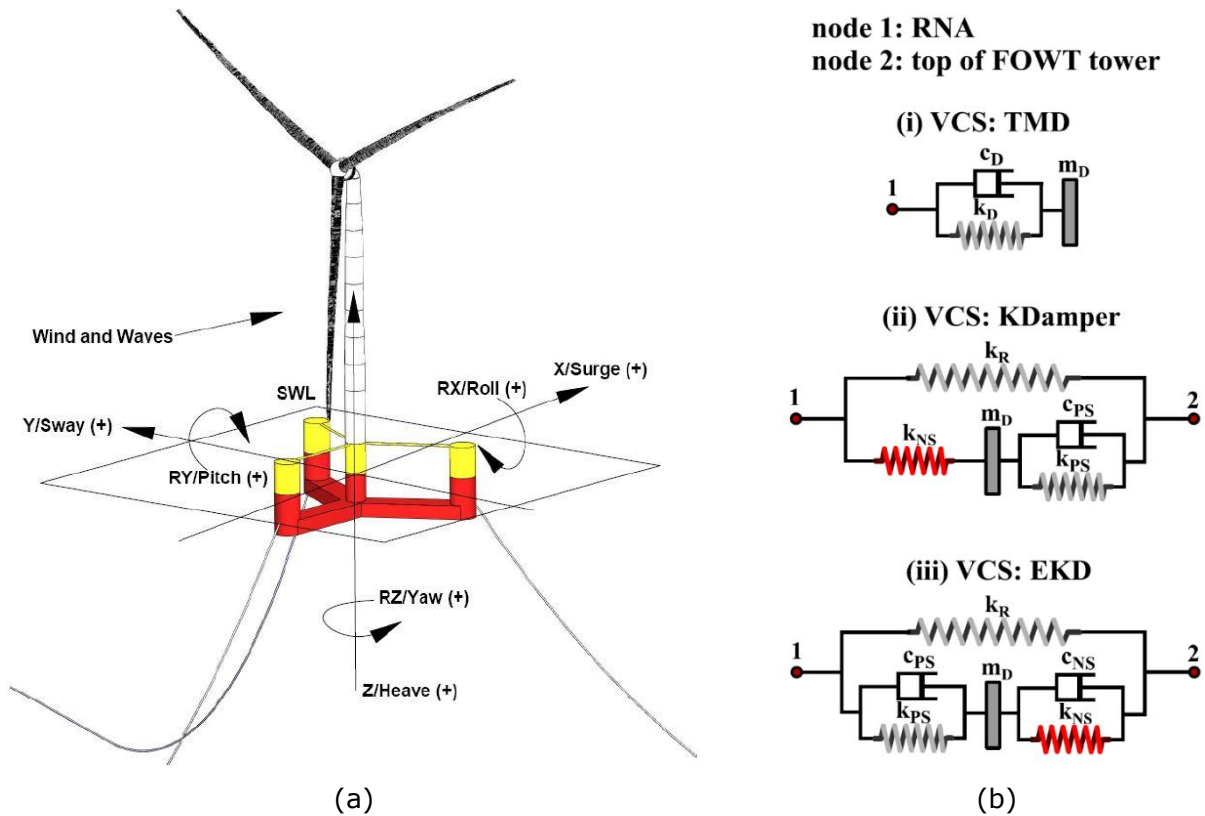


Figure 1. Benchmark FOWT configuration adopted in the present study: (a) general arrangement of the FOWT and reference coordinate system (Allen et al, 2020), and (b) schematic representation of the VCS (TMD, KDamper, EKD) installed between the RNA and the tower

From a structural dynamics perspective, the tower is the primary vibration-sensitive component of the system, exhibiting dominant fore-aft and side-side bending modes that are strongly excited by wind and wave loading. In the present study, the RNA is modeled as a concentrated mass located at the hub height, accounting for the inertial contribution of the nacelle, rotor, and blades. The floating platform is modeled as a rigid body with translational and rotational degrees of freedom, whose inertial, damping, and restoring characteristics introduce low-frequency

motion coupling with the tower response. This modelling choice allows the investigation to focus on the FOWT global vibration characteristics and the effectiveness of the proposed VCS, without introducing unnecessary hydrodynamic complexity. The structural response is described through a reduced-order dynamic model that captures the dominant global vibration behavior of the system. The reduced-order model has been calibrated against OpenFAST through free-decay pitch tests, showing very good agreement. In the present study, the analysis is restricted to the fore-aft direction, while second-order (P-Δ) effects associated with large displacements and axial loading are explicitly accounted for. The FOWT is subjected to the combined action of wind and wave loading, allowing the assessment of the proposed vibration absorbers under realistic offshore operating conditions. This modeling approach enables a focused evaluation of the vibration mitigation performance while retaining the essential nonlinear characteristics of the system. The main geometric and inertial characteristics of the reference FOWT are summarized in Table 1.

Table 1. Key properties of the benchmark floating offshore wind turbine (FOWT)

Property	Symbol	Unit	Value
Rated power	P_r	MW	15
Rotor diameter	D_R	m	240
Hub height above SWL	H_{h-SWL}	m	150
Rotor-nacelle assembly mass	m_{RNA}	t	991
Tower mass	m_{TWR}	t	1263
Total turbine mass	m_{TOT}	t	2254
Dominant vibration modes	-	-	Fore-aft, side-side

2.2 Introduction of negative stiffness VCS

The NS-based VCS considered in this study are installed at the interface between the RNA and the top of the steel tower, as schematically illustrated in Figure 1(b). This location is selected because it coincides with the region of maximum modal participation of the dominant fore-aft bending mode, allowing the vibration absorber to interact effectively with the global structural response. The VCS introduces an oscillating mass m_D between the nacelle and the tower through a combination of positive stiffness, negative stiffness, and viscous damping elements.

The NS element generates a controlled NS force that acts in phase with the inertia force of m_D , increasing its effective inertia. The positive stiffness element ensures stability and limits relative displacements between the nacelle and the tower, while the damping element dissipates vibrational energy. Two VCS are examined, namely the KDamper and the EKD, which differ in the arrangement of the stiffness and damping elements but share the same installation position and operating principle. The equations of motion of the FOWT are formulated in a matrix form, describing the dynamic response of the platform, tower, and VCS in the fore-aft direction:

$$\begin{bmatrix} \mathbf{M}_t & \mathbf{M}_{t-pl} \\ \mathbf{M}_{pl-t} & \mathbf{M}_{pl} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{u}}_t \\ \ddot{\mathbf{u}}_{pl} \end{bmatrix} + \begin{bmatrix} \mathbf{C}_t & \mathbf{0} \\ \mathbf{0} & \mathbf{C}_{pl} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{u}}_t \\ \dot{\mathbf{u}}_{pl} \end{bmatrix} + \begin{bmatrix} \mathbf{K}_t(u) & \mathbf{K}_{t-pl}(u) \\ \mathbf{K}_{pl-t}(u) & \mathbf{K}_{pl}(u) \end{bmatrix} \begin{bmatrix} \mathbf{u}_t \\ \mathbf{u}_{pl} \end{bmatrix} = \begin{bmatrix} \mathbf{P}_t(u) \\ \mathbf{P}_{pl}(u) \end{bmatrix} \quad (1)$$

In contrast to fixed-bottom configurations, the contribution of the floating platform is explicitly accounted for through the introduction of the platform-related mass, damping, and stiffness matrices, denoted as $\mathbf{M}_{pl}$, $\mathbf{C}_{pl}$, and $\mathbf{K}_{pl}$, respectively. The implementation of the investigated VCS is achieved through appropriate modifications of the tower-related mass, damping, and stiffness matrices, $\mathbf{M}_t$, $\mathbf{C}_t$, and $\mathbf{K}_t$, respectively. This formulation allows the VCS to be consistently incorporated into the global system equations of motion without altering the underlying platform representation, providing a unified framework for modeling both the uncontrolled and controlled configurations.

3. OPTIMIZATION FRAMEWORK FOR NEGATIVE STIFFNESS-BASED ABSORBERS

The effectiveness of vibration control systems incorporating negative stiffness (NS) mechanisms is strongly influenced by the selection of their mechanical parameters. In the present study, the NS element is realized exclusively through a pre-stressed spring configuration, which introduces inherent nonlinearities and parameter interactions that preclude closed-form optimal solutions [Kapasakalis et al, 2021]. Consequently, a numerical optimization framework is adopted to identify efficient and physically admissible designs. The optimization procedure is applied independently and consistently to each examined VCS, ensuring a transparent and objective evaluation of their performance and enabling a fair comparison between alternative VCS.

3.1 Design variables and constraints

The VCS are described by a set of design variables governing their inertial, stiffness, and dissipation characteristics. The auxiliary mass is expressed through a dimensionless mass ratio:

$$\mu = \frac{m_D}{m_{RNA}} \quad (2)$$

where m_D denotes the auxiliary mass of the VCS and m_{RNA} represents the effective mass of the rotor-nacelle assembly. This formulation allows direct comparison between different vibration control configurations and avoids bias associated with absolute mass values. The stiffness characteristics of the NS-based VCS are defined by a positive stiffness component k_R , which ensures static equilibrium, and an equivalent NS component k_{NS} generated by the pre-stressed spring mechanism. Energy dissipation within the control system is introduced through the viscous damping coefficients c_{NS} and c_{PS} . These parameters collectively define the mechanical behavior of the VCS and constitute the design variables of the optimization problem.

The admissible design space is defined by a set of stability and feasibility constraints, which are imposed to ensure physically meaningful and practically implementable vibration control designs. The constraints applied in the optimization process can be summarized as follows:

- Stability assurance constraint: due to the presence of the NS element, static and dynamic stability is explicitly verified by requiring a positive determinant of the global stiffness matrix under conservative parameter variations:

$$\det \mathbf{K}(k_{NS}^{lim}, k_{PS}^{lim}, k_R^{lim}) > 0 \quad (3)$$

where $k_{NS}^{lim} = (1 - \varepsilon_{NS})$, $k_{PS}^{lim} = (1 - \varepsilon_{PS})$ and $k_R^{lim} = (1 - \varepsilon_R)$, accounting for possible deviations ε of the stiffness parameters from their nominal optimal values.

- Displacement constraints: the relative displacement between the auxiliary mass and the tower top (VCS stroke) is limited to $\leq 15\text{cm}$ [Kapasakalis et al, 2021], as NS mechanisms are physically realizable within this displacement range. An additional displacement constraint is placed in the RNA stroke, which is limited to $\leq 50\text{cm}$, preventing mechanical interference and ensuring operational safety.
- NS bound: the maximum value of the NS element is limited in accordance with mass-scaled bounds reported in [Kapasakalis et al, 2021], in order to avoid excessive stiffness compensation and potential loss of equilibrium. The NS is constrained per 10^3 kg of superstructure mass, and a NS parameter ranging from 0 to 1 is introduced:

$$\kappa_{NS} = \frac{k_{NS}}{100m_{RNA}} \quad (4)$$

- Damping bounds: upper limits are imposed on the damping coefficients associated with the negative (c_{NS}) and positive stiffness elements (c_{PS}), in accordance with mass-scaled bounds reported in (Kapasakalis et al, 2021), to ensure realistic mechanical behavior and feasible implementation of the VCS:

$$c_{NS}, c_{PS} \leq 2000 \text{ kNs/m} \quad (5)$$

The practical realization of the NS mechanism is based on a pre-stressed spring configuration [Kapasakalis et al, 2021]. Applicability is ensured through the imposed displacement, stiffness, and damping constraints, while robustness under parameter uncertainties is partially addressed through the adopted stability verification under conservative stiffness variations.

3.2 Objective function and optimization procedure

The objective of the optimization is to mitigate the structural demand imposed on the wind turbine tower under dynamic excitation. To this end, the objective function is defined so as to minimize the maximum bending moments and shear forces developed along the height of the tower. These response quantities are directly associated with governing structural design limit states and fatigue performance of FOWT. For each candidate design, nonlinear time-domain simulations of the wind turbine-VCS-platform model are performed. The resulting constrained optimization problem is solved using the Harmony Search (HS) algorithm (Geem et al, 2001).

In the present study, the m_D of the NS-based VCS is selected to be equal to 0.1% of m_{RNA} . By contrast, the TMD is assigned a substantially higher mass ratio of 5%. This distinction highlights a fundamental advantage of the proposed NS-based VCS, namely their ability to achieve effective vibration mitigation with significantly lower auxiliary masses. For the KDamper and EKD configurations, the stiffness parameters, and damping coefficient are obtained directly from the optimization process, while the TMD is tuned to the fundamental fore-aft bending frequency of the tower, and its damping ratio is determined numerically using the same optimization framework with the NS-based VCS in order to minimize the tower structural response.

4. NUMERICAL RESULTS

This section presents selected numerical results obtained from nonlinear time-domain simulations of the FOWT equipped with optimally designed VCS. The structural response of the uncontrolled FOWT is compared against the KDamper and EKD, both with an auxiliary mass ratio of 0.1%, as well as a TMD with a mass ratio of 5%. The simulations account for the combined action of wind and wave excitations representative of offshore operating conditions.

4.1 Envelopes of bending moments and shear forces

Figure 2 illustrates the envelopes of the bending moments and shear forces developed along the height of the steel tower for the uncontrolled FOWT and the three VCS. The introduction of VCS results in a substantial reduction of both bending moments and shear forces throughout the entire tower height. Among the examined configurations, the EKD consistently achieves the greatest reductions, followed by the KDamper and the TMD. These results demonstrate that NS-based VCS can suppress global structural demands more efficiently than conventional mass-based absorbers, even when operating with significantly smaller auxiliary masses.

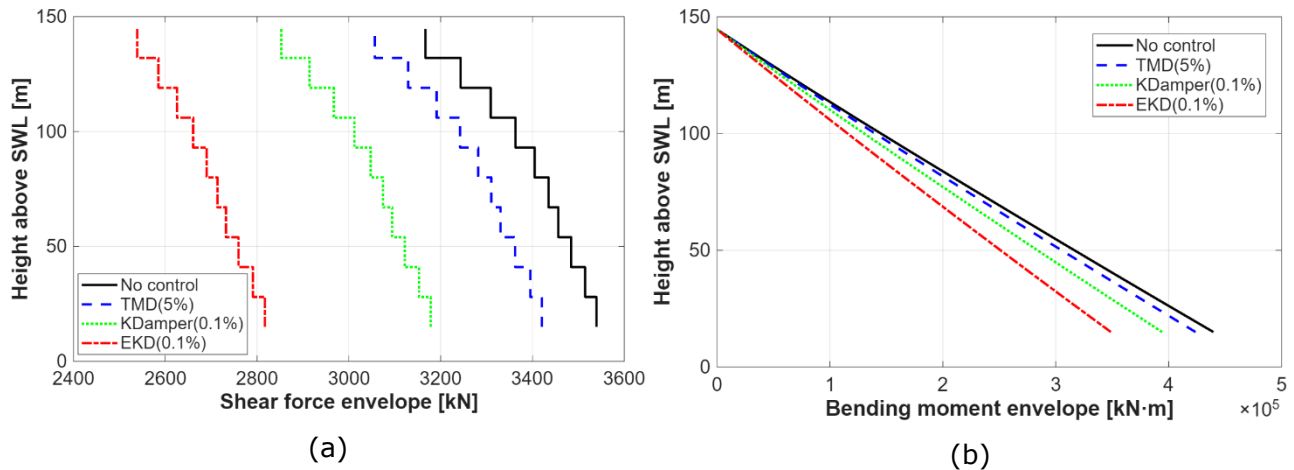


Figure 2. Envelopes of (a) bending moments and (b) shear forces for the uncontrolled FOWT and the KDamper (0.1%), EKD (0.1%), and TMD (5%), under wind and wave excitations

4.2 Time-domain responses

To further investigate the dynamic behavior of the system, Figure 3 presents representative time histories of the tower-top displacement. The responses plotted in Figure 3 correspond to the uncontrolled FOWT and the configurations with the EKD (0.1%) and TMD (5%). The implementation of vibration control systems leads to a clear attenuation of the response amplitudes. In particular, the NS-based system (extended KDamper) significantly reduces the oscillation amplitudes of the tower-top displacement.

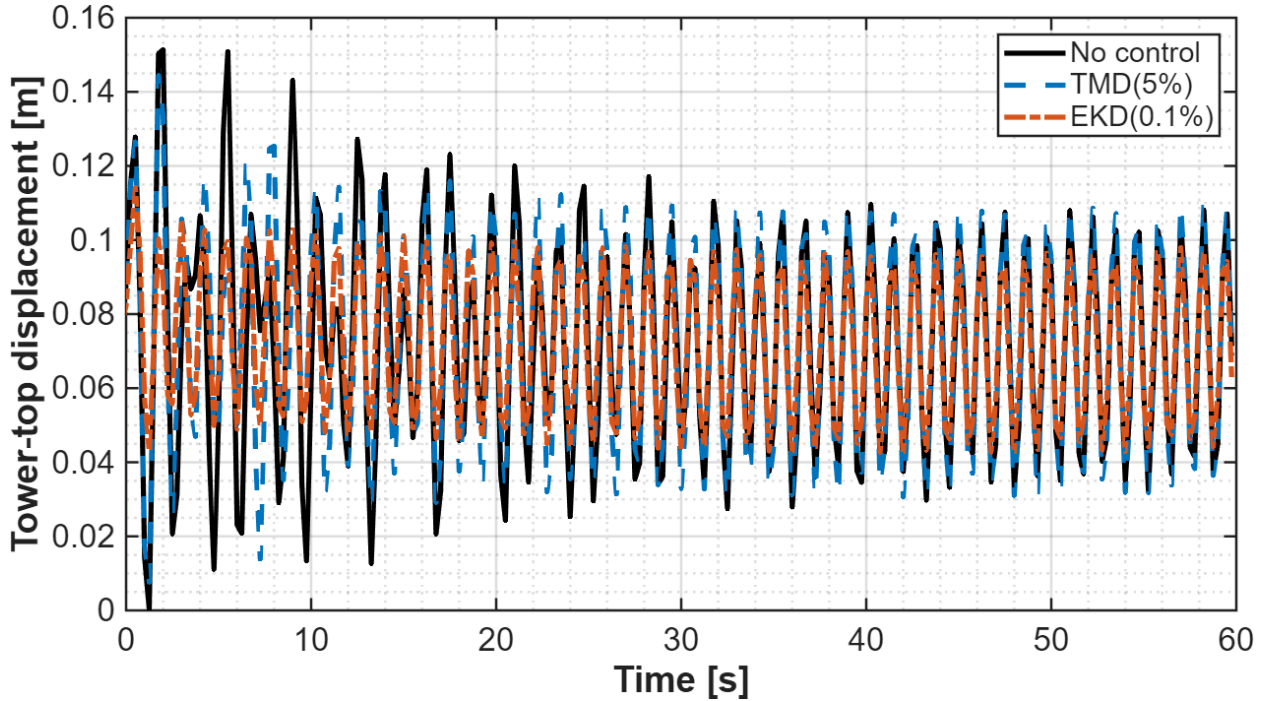


Figure 3. Time histories of (a) tower-top displacement and (b) platform pitch for the uncontrolled FOWT and the KDamper (0.1%), EKD (0.1%), and TMD (5%)

Consistent with the envelope results, the EKD is the most efficient in reducing response amplitudes followed by the TMD. Overall, the numerical results confirm that NS-based VCS constitute an effective and lightweight solution for mitigating vibrations in FOWT, as both NS-based systems have 50 times lower additional mass compared to the TMD. In particular, the EKD emerges as the most efficient, while the KDamper also exhibits a clear advantage over the TMD in terms of vibration mitigation efficiency. The VCS is tuned close to the dominant fore-aft vibration frequency, with optimal performance at slightly lower frequencies. Due to the presence of negative stiffness, reduced sensitivity to detuning is achieved, while performance under other excitation types (e.g., seismic) requires further investigation.

5. CONCLUSIONS

In this study, the effectiveness of NS-based VCS for mitigating the dynamic response of FOWT was investigated. A large-scale FOWT was adopted as a benchmark system, and its fore-aft dynamic response under the combined action of wind and wave excitations was examined. Two NS-based VCS, namely the KDamper and the extended KDamper (EKD), were optimally designed using a unified numerical optimization framework and compared against a TMD employed as a benchmark. The optimization focused on minimizing structural responses directly associated with structural design limit states, namely the bending moments and shear forces developed along the tower. The numerical results demonstrated that both NS-based systems significantly reduce the structural demands of the tower compared to the uncontrolled FOWT. Among the examined configurations, the EKD consistently exhibited the highest vibration mitigation performance, followed by the KDamper and, subsequently, the TMD. Effective vibration mitigation was achieved with auxiliary masses that are more than one order of magnitude smaller than those

required by TMDs (50 times). The time-domain and envelope-based results further indicated that the benefits of the EKD and KDamper are not limited to peak response reduction but extend to the overall system dynamic behavior. Overall, the findings underline the potential of NS-based VCS as efficient and structurally attractive alternatives to conventional mass-based VCS. The proposed framework provides a systematic basis for their optimal design and comparative assessment, contributing to the development of advanced VCS for next-generation FOWT.

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