Improving Floating Wind Turbine Stability with Evolutionary Computation for TMD Optimization

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Abstract: Wind turbines in general allow the conversion of wind kinetic energy into electrical energy, but their installation on land is becoming increasingly complicated, due to wind speed, lower energy generation, environmental, acoustic and visual aspects, land use, among others. In this sense, offshore wind generation has advantages such as stronger and more constant winds, lower visual and acoustic impact, greater generation capacity, development close to large cities, among others. Offshore wind turbines have great potential to transform the global energy matrix, especially with the use of floating platforms that enable energy generation in deep waters. However, these systems face significant challenges, such as pendulum loads and movements induced by winds and waves that cause fatigue to the structure. This work proposes the use of evolutionary computing techniques, through genetic algorithms, to optimize a passive structural control with tuned mass damping devices (TMDs), installed in the nacelle of Floating Offshore Wind Turbines (FOWTs) of the Barge type, aiming to mitigate these pendular effects. The TMDs are configured to act in the fore-aft and lateral-lateral directions, and the optimization considered the standard deviation of the tower fatigue as a fitness function, in addition to including stroke limits to adapt to the nacelle dimensions. The optimization was performed under the free decay condition, i.e., simplified conditions and application of initial inclinations to the platform. The simulations, conducted in the FAST-SC (Fatigue, Aerodynamics, Structures, and Turbulence – Structural Control) software, demonstrated a reduction of more than 36% in the structural fatigue of the tower compared to systems without structural control and an improvement of more than 11% compared to systems with unidirectional TMD. The results reinforce the effectiveness of passive structural control with bidirectional TMD in mitigating vibrations and increasing the reliability of floating offshore turbines, offering an efficient approach to improve the structural reliability of the system.

1 INTRODUCTION

The growing demand for renewable energy sources has driven the development of offshore wind turbines as a promising alternative for electricity production. Although these wind turbines are installed on floating platforms, designed to exploit stronger and more consistent winds in deep waters (60m to 900m depth), they face significant challenges such as wind and wave-induced pendulum loads (Vijfhuizen, 2006), shown in Fig. 1. Floating Offshore Wind Turbines (FOWTs) can have diverse types of bases for buoyancy, with the Barge being a stable, economical, and advantageous option for great depths (Villoslada et al., 2022), therefore chosen for the simulations in this project.

Research in the field of FOWTs aims to improve energy production and avoid negative interference from wind and waves by controlling vibrations and reducing structural fatigue (Olondriz et al., 2019). To this end, various forms of structural control have been explored over the last decade. Passive control using Tuned Mass Dampers (TMDs) is one of the most promising for FOWTs when installed in the nacelle,

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the uppermost and heaviest part of the wind turbine (Zuo et al., 2020).

In all projects, the TMD design is optimized to reduce vibrations and improve wind turbine performance. Parameters such as stiffness, damping and mass are adjusted for this purpose. Adjustment methods include frequency adjustment, genetic algorithms (GA's) and surface graphs. The limitations in the TMD course are little explored, commonly assuming fixed and simplified values, in addition to using reduced models of the system in the optimization loop (Chen et al., 2021). Only one work (Villoslada et al., 2022) used GA for optimization including TMD travel limitation and stop configuration as variables. Although it achieved satisfactory results in the simulation, it only considered forward-reverse TMD, did not consider the side-to-side TMD, nor did it include its variables in the optimization cycle.

In this context, this work aims to optimize, using an evolutionary algorithm, a passive structural control system consisting of two TMDs installed in the nacelle of a barge-type FOWT, in the fore-aft and lateral directions. A genetic algorithm is used to adjust the TMD system parameters, such as mass, stiffness, damping, stroke limitation, and stop variables, with the objective of mitigating vibrations in the structure, platform tower pitch, and turbine bending mode. In the optimization cycles and FOWT tests, the simulation is performed with FAST-SC (Fatigue, Aerodynamics, Structures, and Turbulence – Structural Control) software, considering the free decay of the system.

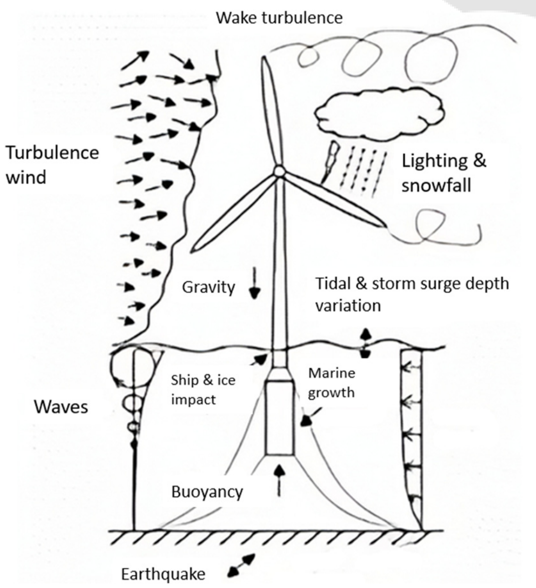

Figure 1: External forces acting on a FOWT (Butterfield et al., 2007).

This work is organized as follows: Section 2 presents the theoretical framework and literature review, Section 3 presents the proposed methodology, Section 4 shows the results obtained, finally Section 5 addresses the conclusions.

2 LITERATURE REVIEW

Most wind power generation is conducted by three-blade horizontal-axis wind turbines located in sparsely populated coastal areas or on onshore fields (Picolo et al., 2014). These turbines consist of blades, rotor (hub), gearbox, generator, nacelle, support tower, and brake system. The nacelle houses essential components such as the gearbox and generator, while the support tower elevates the turbine to optimal heights for energy generation. The brake system controls blade speed, especially during storms. They also have a direction sensor to orient the blades to capture the best frontal wind (Figueiredo, 2019).

2.1 Offshore Wind Turbines and Their Technologies

In recent years, there has been a gradual shift towards offshore wind energy due to favourable wind resources and proximity to coastal urban areas. Offshore turbines take advantage of higher and less turbulent wind speeds, providing greater energy efficiency. They share technology with onshore turbines with structural adaptations for different water depths (Costoya et al., 2020). Fixed turbines in shallow waters present complexity and excessive costs, as well as environmental impacts and space limitations. On the other hand, floating turbines in deep waters (60m to 900m depth) offer reduced costs, simplified assembly, and less environmental impact, making them more viable for offshore deployment (Hu & He, 2017).

FOWTs offer the flexibility of installation at various ocean depths, up to 900m, expanding the possibilities for deployment sites. They are categorized into Barges, Spar Buoys, and Tension Leg Platforms (Villoslada et al., 2022). The Barge is stable and mobile, equipped with fin plates to avoid stresses on the structure, while the Spar Buoy is challenging for fabrication and installation due to its weight concentrated at the lowest point. The Tension Leg Platform is more innovative and riskier, submerged with a star-shaped geometry. The stability of the floating base is ensured by anchoring elements such as mooring and tensioning, with three main types: catenary, mechanically tensioned moorings, and Tension Leg Platform (TLP) anchors (Jonkman, 2007).

Among these options, Barge-type platforms, stabilized by flexible or catenary mooring, are more promising and economical for deep waters (Chen et al., 2021). For this study, the NREL 5MW turbine supported by the ITI Energy Barge, developed by the National Renewable Energy Laboratory (NREL) - USA, was chosen. An illustration of the barge with the NREL 5MW turbine is shown in Fig. 2.

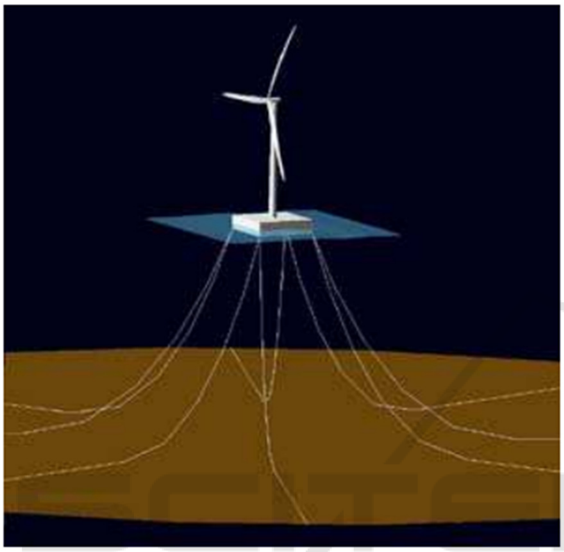

Figure 2: FOWT NREL 5MW and ITI Energy Barge (G. M. Stewart, 2012).

2.2 Structural Control

Structural control aims to reduce loads on buildings and bridges due to waves and earthquakes (G. M. Stewart, 2012). For wind turbines on barge-type floating platforms, this control is crucial due to movements induced by waves and winds, which generate an inverted pendulum effect and structural fatigue. There are three categories of control methods applied to FOWTs: pitch control, active structural control, and passive structural control. Pitch control adjusts aerodynamic forces but has disadvantages in reducing other loads. Active structural control directly restricts vibrations. Passive structural control, such as the Tuned Mass Damper (TMD), is more robust and economical, being widely used in skyscrapers and offshore platforms (Jonkman, 2007).

The Tuned Mass Damper (TMD) is a common passive device used in structural control. It consists of a mass connected to the main structure by a spring and a damper, tuned to vibrate at the system's loading frequency. This vibration allows the damper to dissipate energy in the form of heat, reducing structural vibrations. In addition to the main variables (mass, stiffness and damping coefficient), other design factors influence the performance of the TMD in FOWTs. The installation position (nacelle, tower or platform) affects the frequencies and magnitudes of the loads, while the direction of movement (front-back, lateral or mixed) depends on the type of vibration to be attenuated. The range of movement is limited by the space available for installation, and the travel limits, composed of additional springs and dampers, restrict the mass travel.

The optimal tuning of TMD parameters can be challenging, especially for nonlinear structures such as offshore wind turbines. The effectiveness of the TMD is linked to its mass, but the available space in the nacelle is a significant limitation for its installation. The introduction of additional stops and limiters increases the system's complexity, requiring advanced algorithms and numerical approaches for defining and optimizing FOWT systems with TMD (G. Stewart & Lackner, 2013).

2.3 Evolutionary Computation

Evolutionary algorithms have been widely adopted to optimize TMD parameters due to their ability to manage the complexity of passive structural control systems (Villoslada et al., 2022). These algorithms, inspired by species evolution and genetics, offer an adaptive search mechanism, utilizing a population of problem solutions and genetic operators such as crossovers and mutations to produce results. The fittest are selected for reproduction each generation, combining characteristics from the parents. The basic procedure of the genetic algorithm (GA) involves population initialization, fitness calculation, selection, crossover, mutation, and the creation of a new population until a stopping condition is reached (Faletti Almeida, 2007), as shown in Fig. 3. The problem representation is done through a set of parameters encoded in a chromosome, which is decoded to build the actual solution (individual).

In the GA process, evaluation is essential to assign everyone in the population a numerical value corresponding to their ability to solve the problem. Crossover involves exchanging parts of the chromosomes of two individuals to generate novel solutions, while mutation consists of randomly changing the values of the genes in the chromosomes, ensuring diversity in the population (Faletti Almeida, 2007). The evolution parameters that affect the performance of the genetic algorithm include population size, crossover rate, mutation rate, and generation interval. Proper adjustment of these parameters is essential for efficient search. Performance evaluation is done through evolution curves (Fogel et al., 2000). In this study, genetic algorithms are used to optimize the parameters of the passive structural control type TMD in barge-type FOWTs.

```
Start
t→1
Initialize Population P(t)
while (not end condition) do
t→ t+1
select population P(t) from P(t-1)
apply genetic operators
evaluate population P(t)
end while
end
```

Figure 3: Basic procedure of a Genetic Algorithm (Faletti Almeida, 2007).

2.4 Related Works

FOWTs have been focus of different recent research efforts aimed at improving system efficiency, especially through structural control to avoid negative interference from wind and waves and to control vibrations. Studies have examined both passive and active control for floating wind turbines, highlighting the use of tuned mass damper devices (Chen et al., 2021). Most of these devices are installed in the nacelle of the turbines, although some research has explored installations in the turbine tower and on barge-type platforms (Chen et al., 2021). The design of these devices involves optimizing parameters to reduce vibrations in the FOWT structure. Simulators such as FAST, developed by NREL, have been used to evaluate passive TMD control solutions in different FOWT configurations (Lackner & Rotea, 2011). Additionally, linear models have been developed to investigate the effects of vibration suppression under a variety of load cases (He et al., 2017).

A new passive structural control method for FOWTs is proposed in (Liao & Wu, 2021), to overcome previous limitations in TMD space. The work includes optimizing a TMD installed in the nacelle, showing that it can significantly reduce structural loads and stabilize power output. TMD parameter tuning is currently done through methods such as frequency tuning, genetic algorithms, and surface plots. The use of genetic algorithms to optimize TMD designs has grown, with promising results in simulations (Lackner & Rotea, 2011).

Although explored the inclusion of stops in TMD models, the optimization of these parameters is still limited, often using simplified system models during the optimization cycle (Costoya et al., 2020). Furthermore, few studies address the use of TMDs both fore-aft and lateral-lateral to mitigate structural fatigue, neglecting stop variables in the optimization process and employing simplified FOWT models (Lackner & Rotea, 2011).

This work proposes the optimization of a passive structural control system with two TMD devices (fore-aft and lateral-lateral) installed in the nacelle, incorporating stroke limitation during the optimization cycle. The performance of these devices is evaluated under free decay conditions using the FAST-SC simulator directly in the optimization process.

3 METHODOLOGY

3.1 Characterization: FOWT and Barge

This work uses a 5MW floating offshore wind turbine developed by the National Energy Laboratory (NREL). With a horizontal axis, three blades and variable speed, designed for position against the wind, with a 126m diameter rotor and 90m hub height, as shown in Table 1. Widely adopted in research, this model is supported by organizations such as Union Upwind and the International Energy Agency, is considered economically viable for FOWT's due to their size (Jonkman, 2007).

Mounted on a barge developed in partnership by the Universities of Glasgow and Strathclyde, together with ITI Energy, the barge is square and ballasted with seawater, anchored by eight catenary lines (Vijfhuizen, 2006), as shown in Table 2. For structural control, we opted for the TMD device, installed in the nacelle, composed of a mass connected to springs and shock absorbers, effective in reducing vibrations. The TMD, vibrating in phase opposite to the structure, reduces vibrational energy, converting it into heat. These systems are tuned to the natural frequency of the structure, generally its first most relevant vibrational mode in the system's response (Villoslada et al., 2022).

Table 1: FOWT NREL-5MW (Chen et al., 2021).

Parameters	Dimensions
Rating	5MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126m, 3m
Nacelle Dimension	18m x 6m x 6m
Hub Height	90m
Cut-In, Rated, Cut-Out Wind Speed	3m/s, 11.4m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rotor Mass/ Nacelle Mass/ Tower Mass	110tons, 240tons, 347.46tons
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)

Table 2: ITI Energy Barge (Vijfhuizen, 2006).

Parameters	Dimensions
Size (W × L × H)	40m x 40m x 10m
Moonpool (W × L × H)	10m x 10m x 10m
Draft, Freeboard	4m, 6m
Mass, including Ballast	5,452,000kg
Center of Mass (CM) below SWL	0.282 m
Roll Inertia about CM	726,900,000 kg·m²
Pitch Inertia about CM	726,900,000 kg·m²
Yaw Inertia about CM	1,453,900,000 kg·m²
Anchor (Water) Depth	150m
Neutral Line Length Resting on Seabed	250m
Line diameter	0.0809m
Extensional line stiffness	589,000,000 N

3.2 Parametrization of TMD's

The main parameters of the TMDX (forward-reverse direction) are: mass mT (kg), where a greater mass increases inertia and stored kinetic energy, limited by the total mass of the structure; spring stiffness kT (N/m); damping dT (N·s/m); position xT (m), which influences design loads and constraints; orientation (front-back or side, side-side); and travel limits (stops to limit the movement of the TMDX, affecting loads and restrictions). The barge model considers platform compliance, with tower and TMDX degrees of freedom, in addition to the launch degree. In this context, the following sub-indices are used: TMDX (T), tower (t), stops (S) and barge-type platform (p). The complete TMDX model is illustrated in Fig. 4.

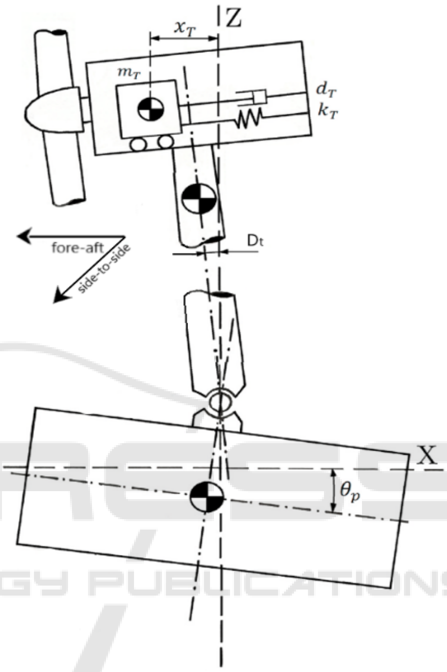

Figure 4: Complete system model for TMDX. Adapted from (Villoslada et al., 2022).

The TMDX stops, or stops limit the displacement of the resonant mass, making the installation viable and realistic. They consist of an additional spring and a shock absorber that come into action when the mass deviates a certain distance from the rest position. Stop parameters include actuation distance (XS), spring stiffness (kS) and damping coefficient (dS). The operational logic of the stops follows the same performance as the FAST simulator, with the spring always active and the damper only operating when the mass moves away from the rest position (Fig. 5).

The TMDY, with side-to-side direction, has the same parameters as the TMDX, but its location is different, and it is installed to reduce lateral fatigue on the nacelle. Both are arranged in a "cross" shape in relation to the center of the nacelle, having different vertical dimensions.

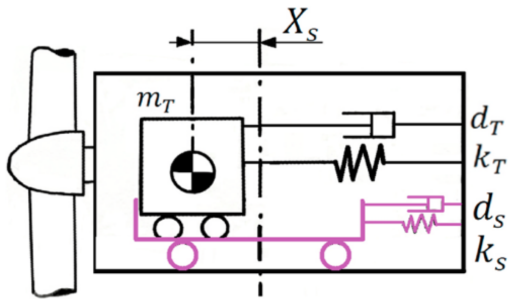

Figure 5: Addition of stops to the TMDX system. Adapted from (Villoslada et al., 2022).

3.3 FAST-SC Simulator

FAST (Fatigue, Aerodynamics, Structures and Turbulence) software simulates a 5 MW wind turbine, using the AeroDyn and HydroDyn modules to calculate aerodynamics and hydrodynamic loads on the floating platform. It employs temporal simulation to solve nonlinear equations, considering varied factors such as axial and tangential induction, tip and hub losses, and dynamic stall modeling (Lackner & Rotea, 2011).

In this simulator, two independent TMDs are integrated for structural control, this modified version of the software being called 'FAST-SC'. The equations of motion are derived using Kane dynamics (Kane & Levinson, 1985). The TMDs are positioned in the wind turbine nacelle and consist of mass, spring, and damper. The position of each TMD, including the neutral spring position, is defined relative to the centerline of the top of the tower, exerting an equal and opposite force on the nacelle. Each TMD has two stroke limiters to restrict movement (Kane & Levinson, 1985).

The TMDs oscillate axially in the turbine nacelle (TMDX) and laterally (TMDY), generating forces. Its equations of motion, derived from FAST, consider positions, velocities, accelerations, and forces. In FAST-SC, TMDX and TMDY are independent and can be controlled in several ways by the user, including passive, semi-active, or active control (Lackner & Rotea, 2011).

The FAST-SC simulator uses an executable file and a main input file. The latter allows the user to modify initial parameters to represent the proposed system, including information about the simulation, wind turbine, buoyancy base (if applicable) and TMD's. It also requires secondary files and libraries for its proper functioning (Fig. 6).

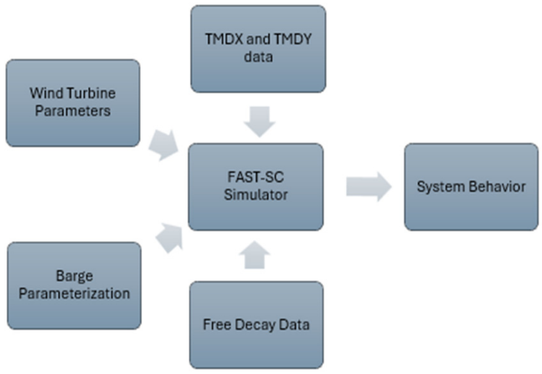

Figure 6: Simplified FAST-SC flowchart.

In the optimization simulations, simplified system conditions were used, including free decay of the structure (wind of 0.5 m/s and without kinematic wave model). The response to an initial displacement of 5 degrees in pitch and 10 degrees of initial yaw rotation on the platform was analyzed. The main parameters include simulation time (one hundred seconds), degrees of freedom (DOF's) of rotation, pitch, and yaw of the platform, as well as the flexion modes are set to 'True' and the initial conditions, shown in Table 3.

Table 3: Main input parameters in FAST.

Parameters	Value
RotSpeed (speed rotor initial)	12.1 (rpm)
TmdXDsp (displacement TMDX initial)	1.0 (m)
TmdYDsp (displacement TMDY initial)	1.0 (m)
PtfmRoll (displacement initial rotation platform)	5 degrees
PtfmPitch (displacement platform initial step)	5 degrees
PtfmYaw (displacement. platform initial lurch)	10 degrees

3.4 Genetic Algorithm Parametrization

In this work, MATLAB software was used with its optimization libraries to encode the genetic algorithm. During the GA optimization cycle, each individual goes through a 100-second simulation in FAST-SC, with free system decay, to analyze their response in relation to the tower deflection in x and y (m) and the barge pitch (degrees). These results make it possible to evaluate everyone's performance in reducing structure fatigue. Each individual is represented by a chromosome with 14 variables, half of which are for the TMDX parameters and the other half for the TMDY parameters. Table 4 contains the description of each variable and its lower and upper limits.

The evaluation function (fa), which determines the fitness of each individual, is based on the deflection of the tower (in meters) on the x (Dtx) and y (Dty) axes, with a weighted average being applied between both. Due to the greatest fatigue occurring in the x-axis [11], the total standard deviation of the evaluation function was calculated according to equation 1.

$$fa = \frac{\sigma(Dtx) \times 9 + \sigma(Dty)}{10} \quad (1)$$

Table 4: Lower and upper limits of optimized parameters.

TMD's Parameters	Low Limit	Upper Limit
TmdXMass (mass)	18,000 kg	42,000 kg
TmdYMass (mass)	8,000 kg	12,000 kg
TmdXSpr, TmdYSpr (spring stiffness)	103 N/m	105 N/m
TmdXDamp, TmdYDamp (damping)	1,000 N.s/m	20,000 N.s/m
TmdXDwSp (stop position - positive axis)	7.5 m	8.3 m
TmdXDwSp (stop position - negative axis)	-8.3 m	-7.5 m
TmdYDwSp (stop position - positive axis)	1.5 m	2.3 m
TmdYDwSp (stop position - negative axis)	-2.3 m	-1.5 m
TmdXSSpr, TmdYSSpr (stop spring)	104 N/m	106 N/m
TmdXSDamp, TmdYSDamp (stop damping)	104 N.s/m	106 N.s/m

Table 5: Main GA evolution parameters.

Parameters	1º	2º	3º	4º
Prossessing Number	12	11	3	5
Population	50	50	15	15
Max. Generations	50	50	30	30
Crossover Rate	0.70	0.70	0.70	0.70
Mutation Rate	0.30	0.30	0.30	0.30
Elitization	5	5	2	3
Stopping Criteria	10-6	10-6	10-6	10-6
Best Individual (fa)	0,2625	0.2714	0,2731	0,2781

Twenty processing of the genetic algorithm were done to obtain the best TMD parameterization results. In Table 5, the main evolution parameters for GA processing that resulted in the four best results are presented.

4 RESULTS

The best individual (solution) among the GA processes was obtained in the 12th process, as shown in the generation versus evaluation function curve in Fig. 7. The curve shows that the best individual reached a value of 0.262508, with an average of 0.262516 per generation.

The graph also shows that GA converged on satisfactory results from the 17th generation onwards, demonstrating its effectiveness in identifying the ideal solution in a relatively short time. This efficiency is fundamental for studies involving multiple interdependent variables, such as TMD parameters, and complex structural analysis conditions.

The use of GA in this study is justified for several reasons. Firstly, the problem in question does not have a defined equation that allows the use of gradient-based methods, making GA an appropriate choice due to its ability to explore large solution spaces without relying on derivatives. In addition, GA simplifies the mathematical representation of the system, allowing the optimization process to be conducted in a more straightforward and intuitive manner. By operating under free decay conditions and with reduced degrees of freedom (DOFs), GA can quickly find the best results for the TMD parameters, maximizing computational efficiency and reducing total processing time.

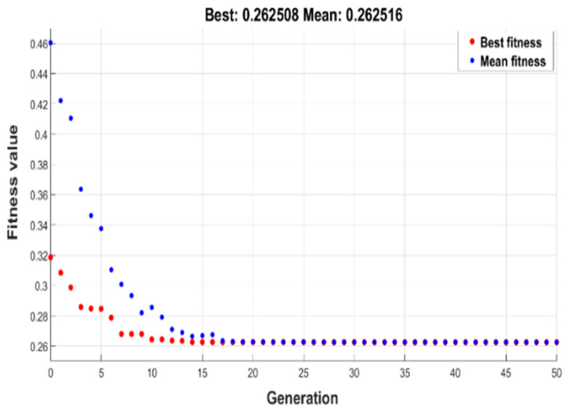

Figure 7: GA behaviour: generations versus evaluation function.

These factors demonstrate the robustness and adaptability of GA as an optimization tool for non-linear and highly complex systems, such as floating wind turbines. GA's ability to find optimal solutions in vast search spaces with multiple constraints reinforces its relevance for future studies seeking to optimize structural control devices under different operating conditions.

The results of the system optimization, with the best parameterizations for TMDX and TMDY, are shown in Table 6. The optimization resulted in a TMDX with a standard deviation of front-to-back deflection of 0.2511 and a TMDY with a standard deviation of side-to-side deflection of 0.3655. These values indicate a significant reduction in the tower's structural vibrations, directly contributing to reduced fatigue in the control devices and the overall structure of the FOWT. This improvement reinforces the effectiveness of optimized TMDs in mitigating oscillations in the main axes, extending the useful life of critical components.

Table 6: Optimized parameters for TMDX and TMDY.

Parameters	*TMDX*	*TMDY*
Mass (kg)	*40,076*	*8,938*
Spring (N/m)	*3,746*	*93,824*
Damping (N.s/m)	*8,607*	*1,006*
Stop Position (m)	*± 8.0*	*± 2.2*
Stop Spring (N/m)	*10,002*	*129,363*
Stop Damping (N.s/m)	*389,954*	*85,957*
σ (tower deflection)	*0.2511*	*0.3655*

In addition, Table 6 shows the main optimized parameters for the TMDX and TMDY devices, which play important roles in the structural control of the FOWT. The 40,076 kg mass of the TMDX allows for greater inertia to reduce front-to-back vibrations, while the spring stiffness (3,746 N/m) and damping (8,607 N.s/m) balance the dynamic response. On the TMDY, the reduced mass of 8,938 kg is suitable for lateral-lateral control, with higher spring stiffness (93,824 N/m) and lighter damping (1,006 N.s/m) due to the different nature of lateral oscillations.

The stop positions (±8.0 m) for TMDX and ±2.2 m for TMDY) and the respective spring and damping parameters of the stops ensure that the displacement of the mass is controlled within safe limits, avoiding overloads on the devices and the structure. These values, calibrated for the specific conditions of the FOWT, demonstrate how optimized parameterization contributes to a more efficient and reliable system.

Figures 8 and 9 highlight a significant improvement in the system's dynamic response after the inclusion of the optimized TMDX and TMDY. Figure 8 illustrates the reduction in the displacement of the fore-aft tower, while Figure 9 shows the reduction in the inclination of the barge.

When compared to the system without any TMD, there is a 36.7% reduction in the root mean square error (RMSE) of the deflection, showing the effectiveness of the optimized devices. This reduction is a clear indication of the mitigation of structural vibrations, which is essential for extending the useful life of the FOWT and reducing maintenance costs associated with structural fatigue. This RMSE value not only reflects a lower oscillation amplitude, but also demonstrates how the optimized TMDs manage to balance the dynamic forces imposed on the system.

This result is visibly highlighted in the graphs, which show a more uniform and consistent attenuation of vibrations compared to the original system. The significant decrease in oscillations reinforces the importance of incorporating optimized passive control solutions, such as the TMDX and TMDY, to improve the stability and operational reliability of floating wind turbines in real operating conditions.

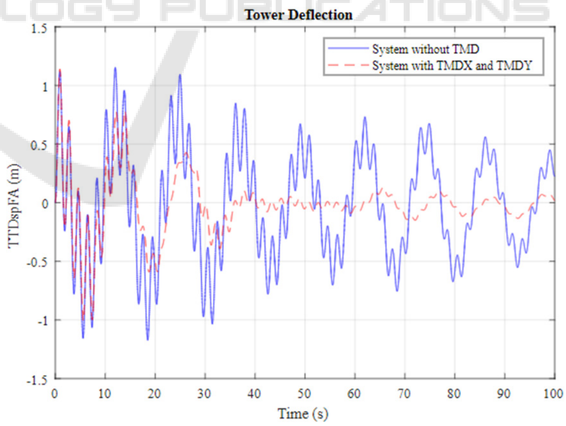

Figure 8: Tower deflection - system without TMD versus system with TMDX and TMDY.

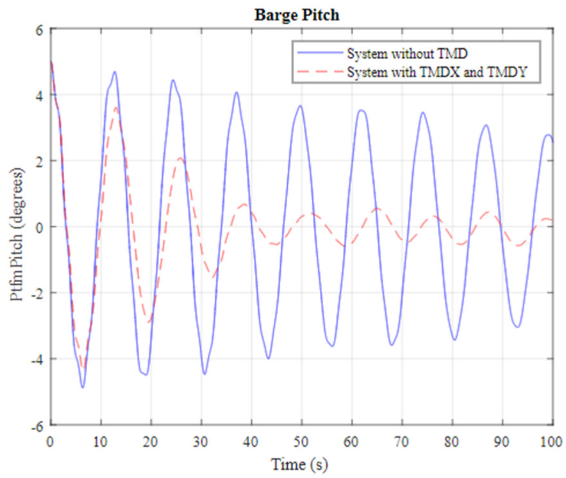

Figure 9: Barge Pitch - system without TMD versus system with TMDX and TMDY.

For comparison purposes, Figures 10 and 11 show the graphs of the front-to-back displacement and lateral displacement of the tower of this system, compared to the results obtained by Villoslada et al. (2022), who optimized only the TMDX under similar initial conditions and free decay.

The analysis shows that the system with bidirectional TMDs (TMDX and TMDY) performed 11% better in terms of RMSE than the unidirectional system optimized by Villoslada. This increase in performance reflects the improved ability of the bidirectional TMD system to mitigate vibrations in multiple directions, contributing to a more balanced reduction in the dynamic forces on the structure.

This superiority of the proposed structural control system is especially important for floating wind turbines, which face complex, multi-directional loads from wind and platform movements. While the unidirectional TMD system focuses on attenuating front-to-back oscillations, the use of bidirectional TMDs allows for a more comprehensive approach, also reducing lateral oscillations, which are critical for avoiding structural failures and reducing tower fatigue.

Figures 10 and 11 visually highlight how the combination of TMDX and TMDY optimizes the dynamic response of the tower, resulting in lower displacement amplitudes in both directions and, consequently, greater reliability and operational stability of the system.

There is a significant improvement in the response of the system that incorporates TMDX and TMDY compared to the system without any TMD, achieving a 36.7% reduction in deflection (RMSE: root mean square error). Furthermore, there was an 11% superior performance (RMSE) compared to the system developed by Villoslada et al. (2022), which optimized only TMDX.

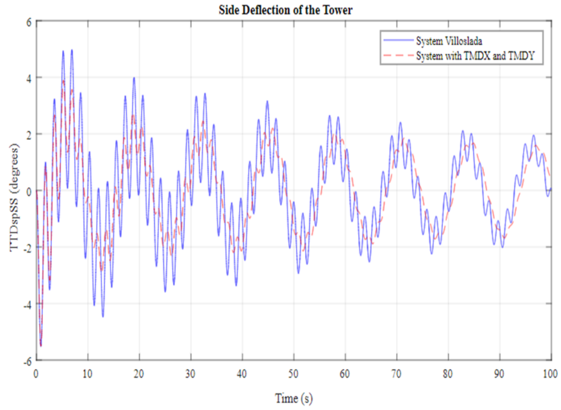

Figure 10: Tower deflection - system with TMDX and TMDY versus results from Villoslada et al. (2022).

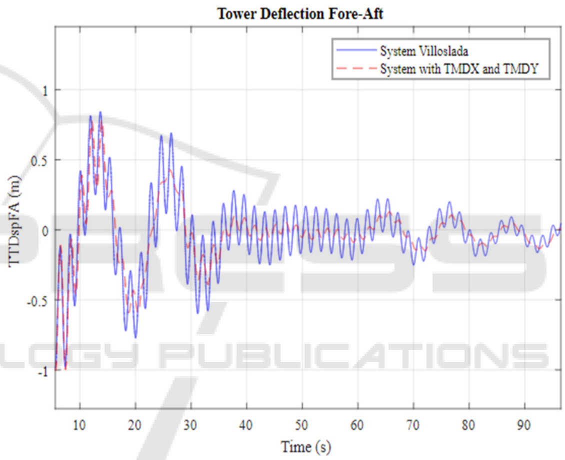

Figure 11: Tower Lateral Deflection - system with TMDX and TMDY versus results from Villoslada et al. (2022).

5 CONCLUSIONS

This study highlights the importance and effectiveness of passive control in reducing vibrations and pendulum loads in floating wind systems, making them more efficient and attractive for energy production. The main contribution of this work is the comprehensive consideration of the parameters of the dual TMD control device in the nacelle, both in the front-to-back and lateral-to-lateral directions, in the optimization cycle, demonstrating that the proposed approach achieves a significant reduction in fatigue (36.7%).

The use of evolutionary computation to parameterize TMDs is recommended, as the results of this study reinforce the effectiveness of the genetic algorithm (GA) as an optimization tool for complex systems such as floating wind turbines. From the 17th generation onwards, GA converged quickly to satisfactory solutions, demonstrating its ability to identify the best TMD parameters under free decay conditions and with reduced degrees of freedom.

In addition, the absence of a defined equation for the problem justifies the use of GA, which simplifies the mathematical representation and makes it possible to explore a wide space of solutions. These factors highlight the relevance of GA for future applications in passive structural systems and highly complex scenarios.

These findings have broad applicability, not limited to barge-type FOWTs. For example, the approach can be adapted to other types of floating platforms, such as Spar Buoys and Tension Leg Platforms (TLPs), which have different structural dynamics and operational challenges. In Spar Buoys, the mass of the TMD could be adjusted to compensate for the high moment of inertia due to the elongated structure. In TLPs, TMDs could be used to deal with the horizontal oscillations generated by the tensioned anchoring forces.

It is worth noting that the integration of the proposed methodology into hybrid platforms, which combine floating elements with fixed foundations, can be explored, extending its applicability to different configurations and maritime environments.

Future work could also include simulations and optimizations under more complex loading conditions, such as turbulent winds and irregular waves, as well as considering TMD devices installed in other parts of the system, such as on the tower or platform, for an integrated control approach. These future directions have the potential to broaden the relevance of the proposed approach and provide more robust solutions for the next generation of offshore wind systems.

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