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Performance of a Single Liquid Column Damper for the Control of Dynamic Responses of a Tension Leg Platform

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Abstract. Tuned liquid column dampers have been proved to be successful in mitigating the dynamic responses of civil infrastructure. There have been some recent applications of this concept on wind turbines and this passive control system can help to mitigate responses of offshore floating platforms and wave devices. The control of dynamic responses of these devices is important for reducing loads on structural elements and facilitating operations and maintenance (O&M) activities. This paper outlines the use of a tuned single liquid column damper for the control of a tension leg platform supported wind turbine. Theoretical studies were carried out and a scaled model was tested in a wave basin to assess the performance of the damper. The tests on the model presented in this paper correspond to a platform with a very low natural frequency for surge, sway and yaw motions. For practical purposes, it was not possible to tune the liquid damper exactly to this frequency. The consequent approach taken and the efficiency of such approach are presented in this paper. Responses to waves of a single frequency are investigated along with responses obtained from wave spectra characterising typical sea states. The extent of control is quantified using peak and root mean squared dynamic responses respectively. The tests present some guidelines and challenges for testing scaled devices in relation to including response control mechanisms. Additionally, the results provide a basis for dictating future research on tuned liquid column damper based control on floating platforms.

1. Introduction

The offshore wind energy industry is moving towards sites which are further from shore in deeper waters and have higher capacity factors and [1, 2]. In such sites where the water depth is greater than 50m floating platforms are considered to be cost competitive with typical fixed foundations [2, 3]. Whilst currently there is no commercial floating wind farm, significant work has been done developing different supporting platform types. They can be categorized into three main types which have adapted from the offshore oil and gas industry: Spar (ballast stabilized), Tension Leg Platform (TLP) (mooring line stabilized) and Semi-submersible (buoyancy stabilized)[4]. Stabilizing a floating



wind turbine platform is a major challenge because turbines inherently have a large mass in the nacelle and rotor located up to 100m above the sea surface.

TLP platforms are very buoyant and are kept on station by tensioned mooring lines, called tendons, that usually extend vertically to the seabed [4]. The stability of a TLP in the vertical direction is regulated by these tendons which are kept under tension by the buoyancy of the platform, thus reducing the vertical motions [5]. Therefore, TLPs are most suited to deep water sites without significant tidal fluctuation and currents [6] in order to maintain the tension in mooring lines. However, TLP drift motions (surge–sway–yaw motion), due to the action of coupled wind–wave forces, can be significant during extreme weather conditions [7, 8]. These motions could affect the wind turbine performance, accessibility during O&M and ultimately the LCOE (levelised cost of energy) [9].

Damping devices integrated into the TLP structure could improve the response characteristics [10], as they have been proved to be beneficial in reducing the vibrations in civil engineering structures [11-13]. Tuned Liquid Dampers (TLDs) are beneficial in offshore wind energy applications for their high performance and low cost [13, 14] whilst Tuned Liquid Column Dampers (TLCD) is the type of TLD which work on the principle of motion of a liquid column in a U-shaped tube counterbalancing external forces imposed onto the structure. The TLCD is found to be successful way of vibration control when structure is exposed to the wind and earthquake loading [15-17].

Lee et al. [18] studied a pontoon type offshore floating platform which incorporated with a TLCD both numerically and experimentally. This paper extends this work to an experimental structure with a much lower frequency (around 0.33 Hz). However, it is practically difficult to match this frequency due to the very large size of upstands necessary for the TLCD. Consequently, the TLCD is tuned to a close enough frequency of 0.5Hz so that the frequency response in the range of the natural frequency of the structure and that of the TLCD overlap significantly. A smaller structure would perhaps allow for testing with exact tuning to a model with a higher natural frequency and consequently more reasonable size of the upstand. However, for such conditions it is difficult to produce scaled wave conditions at that size in a flume [19]. The TLCD design in this paper is based on that described in Yalla and Kareem [20]. Additionally, variations in damper characteristics are also considered. The results of this study are encouraging and form the benchmark for further investigation of TLCD application in offshore wind energy substructure motion mitigation. The results of the study inspired further investigation of the application of the multiple TLCD (MTLCD) for TLP motion mitigation [10]. Jaksic et al. [10] investigated capacity of MTLCD to mitigate motions of TLCD. They found that the additional weight of the dampers on structure causes the tension of the tendons to decrease. In order to keep the tension in tendons additional buoyancy was added to the system. The consequence was that the TLP with MTLCD could be tested only for the low wave height (e.g. Froude-scaled wave amplitudes, H_s , 0.015, 0.02, 0.025, 0.03, and 0.035m) with single period $T_p=2.4$ Hz in order to remain within load cell capacity. This study shows the results for the wider range of the wave height and period which is in better agreement with the real sea states (e.g. Froude scaled wave amplitudes, H_s , 0.05, 0.075, and 0.1m and T_p , 1.2, 2.4, and 3.6s). To understand the interaction between TLCD and wave energy devices with low natural frequency, a single TLCD-tension leg platform interaction was considered to be an appropriate investigation and this has been addressed in the current paper.

2. Theoretical Modelling

The surge motion of TLP is considered for the simulation studies. Uncoupled linear equation of this motion is given as [18]

$$M\ddot{X} + C_X\dot{X} + K_X X = F_w(t) \quad (1)$$

where M represents of the TLP structure, C_X and K_X are the damping and stiffness associated with the TLP. The wave force from the Pierson Moskowitz (PM) spectra is represented as F_w . X is the motion along the surge direction.

The equation of motion of the system, i.e., TLP with TLCD is given as [18],

$$\rho_d A_d L_d \ddot{H} + \frac{1}{2} \rho_d A_d h_d \left[\dot{H} \right] \dot{H} + 2 \rho_d A_d g H = -\rho_d A_d B_d \ddot{X} \quad (2)$$

$$M \ddot{X} + C_X \dot{X} + K_X X = F_w - \rho_d A_d B_d \ddot{H} - \rho_d A_d L_d \ddot{X} \quad (3)$$

Where h_d is the factor of the head loss of the liquid, H , \dot{H} and \ddot{H} are the displacement, velocity and the acceleration of the liquid in the vertical tube, respectively. ρ_d is the density of the liquid. The geometric parameters of the damper are inner cross sectional area, A_d , length of horizontal section, B_d and L_d being the total length.

The random force F_w is obtained from Pierson–Moskowitz (PM) spectrum using the following equation.

$$F_w(t) = \sum_{i=1}^k A_i \cos(2\pi f_i t - \phi_i)$$

where, $A_i = \sqrt{S(f_i) \Delta f_i}$, A_i is the i^{th} amplitude, f_i is the i^{th} frequency, ϕ_i is the i^{th} phase angle. The value of $\phi_i \in [0, 2\pi]$ are randomly generated using uniform distribution. $S(f_i)$ is the spectral density value of the wave force spectrum at the frequency f_i and $\Delta f_i = 0.1$ Hz is the frequency step considered. A swept sine simulation is carried out to obtain the frequency response of the TLP and TLP with TLCD with different values of the liquid density of the TLCD (m_d^*). Different fluid density is considered to present different fluid within TLCD while keeping all other parameters of the damper constant.

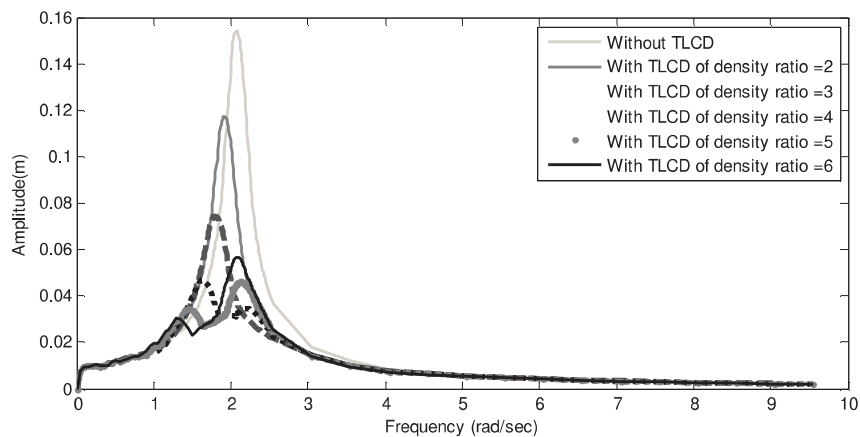


Figure 1: Frequency response results of TLP without and with TLCD.

Figure 1 shows comparative results of the simulation. The frequency sweep is carried out till 10 rad/s. The liquid density ratios were varied from 2 to 6. Responses in the frequency domain were compared with responses which were obtained without the use of TLCD dampers. The responses decrease as m_d^* increases up to $m_d^*=4$ and then again it increases for $m_d^*>4$. The minimum response was observed when m_d^* is between 3 and 4. The displacement responses for TLP with and without TLCD are compared and reported in Figure 2 for different values of density ratio. Forced oscillation was simulated for 150s and then the system is allowed to vibrate freely.

Figure 2 shows the response with TLCD has reduced compared with only TLP. A reduction of 48.6% in peak displacement is obtained using TLCD. Norm value also was calculated, and obtained a reduction from 1.465 to 0.33 (77% reduction)

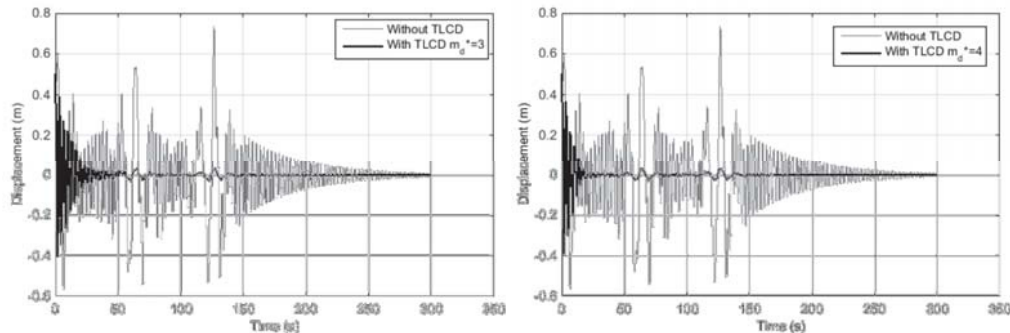


Figure 2: Displacement of the system without and with TLCD for density ratio: a) $m_d^*=3$ and b) $m_d^*=4$.

3. Experiments

3.1. TLP Model with Tuned Liquid Column Damper (TLCD)

The model TLP is a truss type structure with a floating hexagonal platform connected with six mooring tethers to a large circular gravity base located on the floor of the wave basin (Figure 3). The floating hexagonal platform is made up of a buoyancy ring and the upper structure. The buoyancy ring consists of six 90mm diameter Polyvinyl chloride (PVC) pipes, joined to the central column by six 40mm diameter PVC pipes. Situated above the buoyancy ring is the upper structure, fabricated from 40mm diameter PVC pipe, which is joined to the buoyancy ring by six 40mm diameter sections of pipe, and to the central column by six 40mm diameter PVC pipes. The upper structure provides no buoyancy as it is not submerged. The central column is fabricated from 160mm diameter PVC pipe and provides sufficient buoyancy to counteract the weight of the tower and nacelle. The excess buoyancy force ensures that the six mooring lines, made of 2mm diameter stainless steel wire, remain in tension at all times. The weight of the TLP is 16.8kg. The wind turbine tower is 1.15m high 50mm diameter PVC pipe (0.8kg) with the 2.2kg thrust load and a nacelle weight of 0.8kg.

A U-shape TLCD device was attached to the upper structure at the level of the center of the gravity (CG). It was designed following Yalla and Kareem [20] and is tuned to the average frequency of the longest Bredschneider waves the basin can generate (0.59Hz). The effects of two TLCD designs on the behaviour of the structure were studied. In the first case the mass ratio, μ (mass of liquid in the tube (m_d) to the mass of the primary system represented by the platform with the turbine tower (M_s)) was 5%, and in the second case 10%, with pipe diameter 30mm and 40mm, respectively. The horizontal part of the TLCD was 1m long, and the vertical part was 0.6m long (filled with water up to 0.2m) to allow for water movement during testing. The experimental set up of TLP is shown in Figure 3a, while the gravity base with load cell arrangement and position of TLCD in relation to the incident wave direction is shown in Figure 3b.

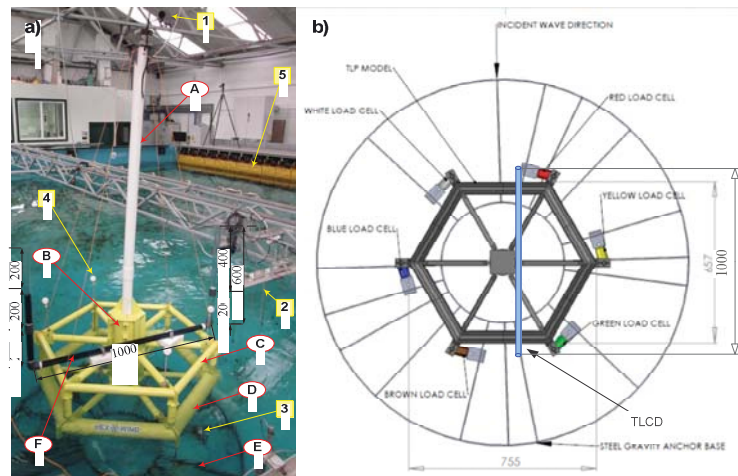


Figure 3: a) 1:50 Scale Model of Truss type TLP Platform experimental setup: (A) mast, (B) central column, (C) upper structure, (D) buoyancy ring, (E) gravity base, and (F) TLCD. The locations of devices used: (1) motion camera, (2) wave probes, (3) load cells, (4) reflective motion markers, and (5) flap type wave-maker; b) TLP view from above: position of TLCD and gravity base with load cell arrangement in relation to the incident wave direction.

3.2. Instrumentation

The TLP equipped with a TLCD device was tested using specified wave conditions and the performance was recorded using six load cells, two conductivity probes, and four motion capture cameras. The Tedeo-Huntleigh stainless steel single ended bending beam load cells measured the tension in mooring tethers in Newtons (with a maximum load of ~50N) and were bolted to the gravity base. Each load cell was given a colour code (name) during the testing, i.e. White, Red, Blue, Yellow, Brown, and Green were located at Bow Port, Bow Starboard, Amidships Port, Amidships Starboard, Stern Port, and Stern Starboard, respectively. Two conductivity probes measured the surface elevations during testing and allowed the incident wave conditions to be determined. In order to measure the motions of the TLP during the testing, four reflective markers were attached to the corners of the hexagonal base. The instantaneous positions of the markers were monitored by the Qualisys 3-Series Oqus Marker Tracking Cameras with a sampling frequency of 32Hz. The load cells and wave probes were triggered by the National Instruments Labview 2011 Version 11.0 software. The Qualisys Marker Tracking system was time synchronised with the other instrumentation using Labview.

3.3. Experimental Procedure

The model testing was carried out in wave basin (25m x 18m x 1m) equipped with 40 flap type paddles capable of generating sinusoidal wave profiles as well as 2 and 3-D wave spectra. The TLP was tested for Bretschneider (BS) and Joint North Sea Wave Observation Project (JONSWAP or JS) spectra, wave periods, T_p , 1.2, 2.4, and 3.6s, considering Froude 1:50 scaled (structural models) and waves with heights, H_s as 0.05, 0.075, and 0.1m respectively.

4. Results and Discussion

The TLP was excited by different waves for about one minute in each test and the dynamic responses were recorded. The results of this experimental work are presented in Figure 4. The comparison of the surge energy measured by yellow load cell between completely undamped (without TLCD) and damped (with TLCD) case for H_s 50 and 75mm are presented in Figure 4a. The results show that the surge energy decreases when a TLCD is installed onto the structure. This observation is in agreement with the numerical modeling results presented in this paper and those obtained by and Lee et al. [18].

Figures 4b-h show the comparison of results for TLP with TLCD for BS and JS spectra for $\mu = 5\%$ and 10% , with and without thrust loading. Figure 4b shows H_s vs. percentage reduction (in relation to undamped case) in tension (+ve means %age reductions in all figures) in yellow cell measurements. The tension reduces with increasing μ for both types of spectra. The presence of the thrust reduces the tension visibly more for BS than JS spectra. The results for BS spectra show that for $\mu = 5\%$ the tension increases with the wave height. However, the results for $\mu = 10\%$ are inconclusive since the tension is reduced for wave height 75mm in comparison with 50mm and 100mm waves. When thrust is present, the tension decreases with wave height. The results for JS spectra show almost the same level of reduction for $\mu = 5\%$ with or without thrust when H_s increases. On the other hand, in the case of $\mu = 10\%$ the tension decreases with wave height increase. Figures 4c-e shows the H_s vs. the percentage reduction in displacement (X), velocity (V), and acceleration (A) RMS, respectively, in relation to the undamped case. For $\mu = 5\%$ the percentage displacement RMS decrease for both wave spectra up to 0.36% for BS wave height 50mm, while for $\mu = 10\%$ they increase up to 0.2% for wave height 75mm. When thrust is present, displacement response increases for both wave spectra were observed with the maximum being -1% for JS. This phenomena was observed by Roderick [14] where numerical analysis for three different offshore wind turbine configurations, including various locations for TLCD installations were carried out and the results indicated that in most cases the TLCD could successfully reduce overall tower displacement and platform pitch. However, in some cases the use of TLCD actually increased the overall tower and platform motions.

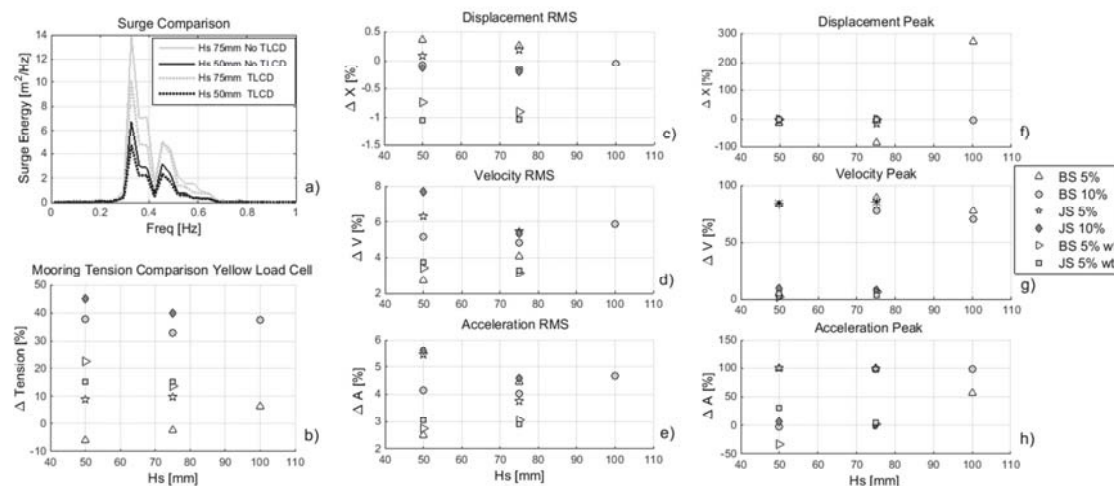


Figure 4: a) Yellow load cell: frequency vs. surge energy for damped and undamped case for 50 and 75mm wave amplitude. b-h) Results for TLP with TLCD for BS and JS spectra when $\mu = 5$ and 10% without and with thrust in comparison with undamped case: b) wave amplitude vs. percentage reduction in tension measured by yellow load cell; c) wave amplitude vs. percentage reduction in displacement RMS; d) wave amplitude vs. percentage reduction in velocity RMS; e) wave amplitude vs. percentage reduction in acceleration RMS; f) wave amplitude vs. percentage reduction in displacement peak; g) wave amplitude vs. percentage reduction in velocity peak; h) wave amplitude vs. percentage reduction in acceleration peak.

The velocity and acceleration RMS is reduced more significantly for higher μ and lower H_s . The presence of the thrust in experiments gives the lowest reduction in the RMS values of velocity and acceleration. Figures 4f-h show the H_s vs. the percentage reduction in peak displacement (X), velocity (V), and acceleration (A). The highest reduction in displacement peak was observed for $\mu = 5\%$, when the platform was exposed to 100mm BS waves. On the other hand, the lowest reduction in displacement peak was observed for $\mu = 5\%$ when the platform was exposed to 75mm BS waves.

However, these two extremes are much different from other results and can be attributed to some leakage of water from TLCD at pipe connections. The displacement peak varies negligibly between remaining measurements, with slightly increased values for $\mu = 10\%$. The velocity peak decreases generally around 80% for BS and JS when $\mu = 5\%$, while it decreases negligibly in other cases. The acceleration peak reduction figures show the same trend with higher reduction in acceleration for BS and JS spectra related to $\mu = 5\%$ as compared to $\mu = 10\%$. The only exception of this is that the contribution of the thrust reduces the peak in the case of JS, while it increases the peak in the case of BS.

5. Conclusions

This paper numerically and experimentally studies the effectiveness of two designs of a single tuned liquid column damper (TLCD) on the dynamic performance of an offshore wind floating tension leg platform (TLP). The numerical studies showed that the reduction in the displacement of the structure is achieved by incorporation of the TLCD. Moreover, the density of the liquid is a factor that can control the level of the reduction of the TLP motion to a certain extent. Testing of the floating offshore wind structures in a wave tank with actual ocean wave spectra confirms that TLCD can reduce the overall motions of the TLP substructures when exposed to such wave conditions. A reduction in the load cell tension measurement has been observed due to installation of TLCD but further studies are required to make a more conclusive observation. The reduction in peak and RMS values for displacement, velocity, and acceleration of the platform has been reported in this paper. This study forms the basis for further investigation of application of TLCD for mitigating dynamic responses of TLPs. The findings of this research encouraged further investigation into employment of multiple dampers for reducing the motions of the TLPs in the extreme weather conditions [10].

The paper emphasizes the importance of using larger scaled model testing in more realistic conditions to assess control or monitoring strategies and designs for full scale deployment. Small scale models do not necessarily capture certain complexities and challenges related to the mitigation of dynamic responses of offshore renewable energy device platforms. These experiments also show that to achieve an optimal arrangement for the control of dynamic responses of TLP, a number of adjustments is required to be undertaken frequently over the lifespan of structure. For structures with low natural frequency, exact tuning of TLCD can be difficult due to geometric constraints but a tuning close to that low frequency can still achieve an adequate level of vibration mitigation.

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