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Dynamic response mitigation of floating wind turbine platforms using tuned liquid column dampers

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In this paper, we experimentally study and compare the effects of three combinations of multiple tuned liquid column dampers (MTLCDs) on the dynamic performance of a model floating tension-leg platform (TLP) structure in a wave basin. The structural stability and safety of the floating structure during operation and maintenance is of concern for the performance of a renewable energy device that it might be supporting. The dynamic responses of the structure should thus be limited for these renewable energy devices to perform as intended. This issue is particularly important during the operation of a TLP in extreme weather conditions. Tuned liquid column dampers (TLCDs) can use the power of sloshing water to reduce surge motions of a floating TLP exposed to wind and waves. This paper demonstrates the potential of MTLCDs in reducing dynamic responses of a scaled TLP model through an experimental study. The potential of using output-only statistical markers for monitoring changes in structural conditions is also investigated through the application of a delay vector variance (DVV) marker for different conditions of control for the experiments.

1. Introduction

A tension-leg platform (TLP) is a floating platform connected to the seabed by vertical tendons or tethers. The tendons are kept in tension due to the buoyancy of the platform. This pretension is designed to keep the tendons under tension under all circumstances, even in large wave conditions [1]. The stiff connection of the platform with the seabed minimizes the vertical motions and gives the platform a short natural period outside of typical sea conditions (typically 2–4 s) [2,3]. However, a TLP is not constrained dynamically in the horizontal direction and the drift motions (surge, sway and yaw motion) of the platform due to the action of coupled wind–wave forces can be significant during extreme weather conditions [3–5]. These motions can influence the performance of a wind turbine, the accessibility during its operation and maintenance (O&M) and ultimately the levelized cost of energy (LCOE) [6,7]. Incorporation of damping devices to the structure has been suggested to reduce these types of responses [2,8–10].

A reasonable method to reduce vibrations of floating platforms is through the use of structural control devices typically employed in civil structures [10–14]. Among many types of structural control devices traditionally available, tuned liquid dampers (TLDs) may be favourable for application in the offshore floating wind energy devices for their relatively high performance and low cost [15–17]. The tuned liquid column damper (TLCD) is a type of TLD that relies on the motion of a liquid column in a U-shaped tube to counteract the action of external forces imposed on the structure. The energy dissipation in the water column is due to the passage of liquid through an orifice with inherent head-loss characteristics [8,18]. The overall damping in a TLCD is nonlinear due to the quadratic damping term [19]. TLCDs have been found to be effective for vibration control when a structure is exposed to wind and/or earthquake loading [14,16,17,20]. Yalla & Kareem [19] used the theory of TLCDs and developed an equivalent linearization scheme to compute the optimum head-loss coefficient for a given wind or seismic excitation in a single step. They used a single degree of freedom system exposed to white noise and a set of filtered white noise load, representing the broadband wind and seismic loading, to determine numerically the optimal damping coefficient and tuning ratio of a TLCD.

Lee *et al.* [8] studied, numerically and experimentally, a typical pontoon-type offshore floating platform with a TLCD. They varied the diameter and the draft of the pontoon as well as the mass of the platform structure in order to evaluate dynamic response mitigation through incorporation of a TLCD. They found that, as long as the parameters were tuned appropriately according to the properties of the main structure, the TLCD exhibited a good performance. They presented analytical evaluation of the pontoon structure motion reduction and experimental response comparison in the time and frequency domains of the platform with and without a TLCD based on experiments on a small model in a wave flume. The analytical results show that the energy dissipated from the TLCD device may reach a value of up to 70% (and in most cases over 50%), while the variations in the draft and dimension parameters indicate the influence of these parameters on the performance of a TLCD. The preliminary experimental results show that this device could be effective for vibration suppression for the floating platform. However, experimentation for larger models and for greater depths of water is required for such platforms along with experimental studies utilizing ocean wave spectra. Gao *et al.* [21] studied the effects of the multiple tuned liquid column dampers (MTLCDs) in suppressing structural vibrations. They found that the frequency range and the coefficient of head loss may have significant effects on the performance of MTLCDs and that increasing the number of TLCDs can enhance the efficiency of the MTLCDs. They showed that optimized MTLCDs are even more sensitive to the coefficient of head loss (or damping) than a single TLCD. However, in order to maintain the same level of efficiency as an optimized single TLCD, MTLCDs offer much wider choices in both frequency ratio and coefficient of head loss. In this sense, MTLCDs are more robust than a single TLCD. Experimental studies for MTLCDs in this regard for floating platforms have not been done.

This study expands the work of Lee *et al.* [8] experimentally and combines it with the theoretical concept of Gao *et al.* [21] through numerical and experimental results related to the effects of MTLCDs on the dynamic responses of a TLP structure. The experiments were carried out in a wave basin on a Froude-scaled (1 : 50) TLP equipped with MTLCDs and capable of supporting a wind turbine structure. Individual TLCDs were designed using the principles described in Yalla & Kareem [19], where the total length of the water column was obtained by equalizing the peak of an irregular wave frequency with the water column frequency. The effects on the structural response of three combinations of two different TLCD designs are tested and compared. The MTLCD combinations relate to three ±5% (MTLCD1), three ±10% (MTLCD2) and two ±5% and one ±10% (MTLCD3) damper to TLP mass ratio (μ). The dynamic responses of the TLP for a closed (inactive) and an open (active) MTLCDs were investigated in the presence and absence (represented as 'thrust' and 'no thrust' conditions, respectively) of mechanically simulated equivalent wind loads at the nacelle. The dynamic response of the TLP was monitored at different locations using load cells and a camera-based motion recognition system. The structure was exposed to scaled sea states characterized by the Joint North Sea Wave Observation Project (JONSWAP) spectra. The percentage of force change in the mooring tendons and percentage change of displacement responses were computed for various combinations and designs of MTLCDs in the presence of varying wave characteristics. A delay vector variance (DVV) method was tested as a potential output-only statistical marker for monitoring structural changes. The results of this study are encouraging and form the basis for further prototype testing and investigation of MTLCD application in offshore wind energy substructure motion mitigation along with the development of output-only statistical markers for monitoring such devices.

2. Experimentation and numerical modelling

(a) Tension-leg platform model with tuned liquid column damper

The TLP platform tested (figure 1) is a truss-type structure with a floating hexagonal platform connected by six mooring tethers to a large circular gravity base which sits on the bottom of the wave basin. The model is scaled according to the Froudian scaling laws and has a scale factor of 50 [22,23]. The floating hexagonal platform consists of the buoyancy ring and the upper structure. The buoyancy ring consists of six 90 mm diameter polyvinyl chloride (PVC) pipes, joined to the central column by six 40 mm diameter PVC pipes. Situated above the buoyancy ring is the upper structure, fabricated from 40 mm diameter PVC pipe, which is joined to the buoyancy ring by six 40 mm diameter sections of pipe, and to the central column by six 40 mm diameter PVC pipes. The upper structure provides no buoyancy as it is not submerged. The central column is fabricated from 160 mm diameter PVC pipe and provides sufficient buoyancy to counteract the weight of the tower and nacelle. The excess buoyancy force is passed to the six mooring lines made of 2 mm diameter stainless steel wire to ensure that they remain in tension at all times. The weight of the TLP is 16.8 kg. The wind turbine tower is 1.15 m high 50 mm diameter PVC pipe (0.8 kg) with the 2.2 kg horizontal thrust load simulating the average effects of wind. Three U-shaped TLCD devices are attached to the upper structure at the level of the centre of the gravity. The middle length TLCD (TLCD1) is designed following Yalla & Kareem [19] and is tuned to the average frequency of the longest JONSWAP waves the basin can generate (0.59 Hz). The other two TLCDs, one longer (TLCD2) and one shorter (TLCD3), are tuned for neighbouring frequencies, 0.70 and 0.53 Hz, respectively, in order to cover a wider spectrum. The effects of the three combinations of the two TLCD designs on the behaviour of the structure were studied. In the first case of TLCD design the mass ratio, μ (ratio of mass of liquid in the tube, m_{d}^{*}, to mass of the primary system, M_{s}), was 5%, and in the second case 10%, with a pipe diameter of 30 mm and 40 mm, respectively. The design characteristics of TLCDs are shown in table 1, while the combinations tested are shown in table 2. Since the higher weight of the MTLCDs in MTLCD2 causes instability of the TLP owing to the reduction in the tendon loads, an additional 17 litres of buoyancy was added to the platform. The added buoyancy was retained throughout the entire experiment in order to obtain comparable results. The experimental set-up of the TLP is shown in figure 1*a*, while the gravity base with the load

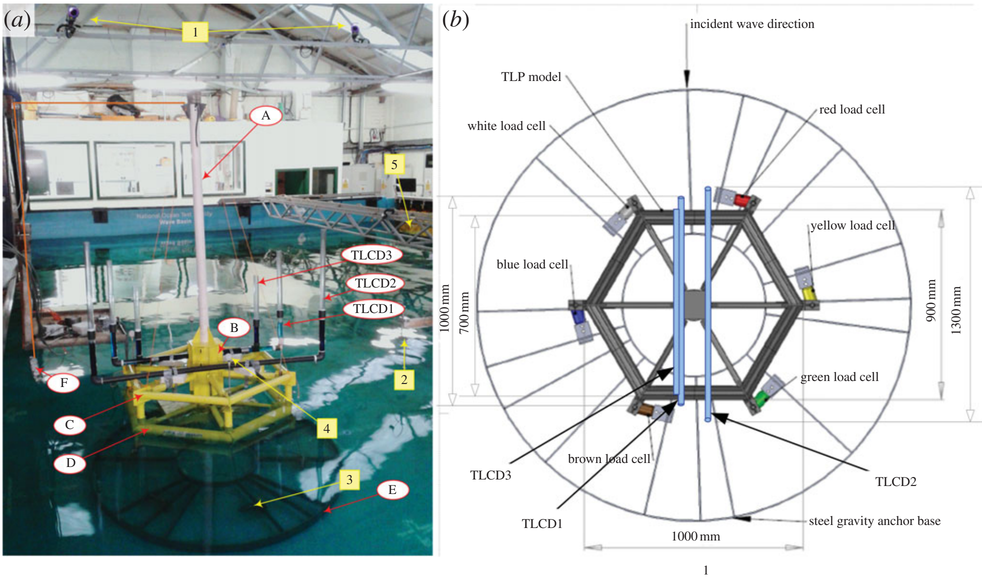

Figure 1. (*a*) 1 : 50 scale model of the truss-type TLP experimental set-up: (A) mast, (B) central column, (C) upper structure, (D) buoyancy ring, (E) gravity base and (F) thrust load. The locations of devices used: (1) motion cameras, (2) wave probes, (3) load cells, (4) reflective motion markers and (5) flap-type wave-maker; (*b*) TLP view from above: position of the MTLCDs and the gravity base with the load cell arrangement in relation to the incident wave direction. (Online version in colour.)

Table 1. TLCD designs.

TLCD	tuned frequencies (Hz)	length of TLCD (m)	horizontal length (m)	vertical length (m)	vertical length extension[a] (m)
TLCD1	0.596	1.4	1.0	2.0	0.4
TLCD2	0.705	1.8	1.3	2.5	0.5
TLCD3	0.525	1.0	0.7	1.5	0.3

[a] The length to prevent loss of water.

Table 2. MTLCD designs.

combinations	mass ratio, μ (%)	TLCD1	TLCD2	TLCD3
MTLCD1	5	✓	✓	✓
MTLCD2	10	✓	✓	✓
MTLCD3	5		✓	✓
	10	✓		

cell arrangement and position of the TLCDs in relation to the incident wave direction is shown in figure 1*b*.

(b) Instrumentation

The performance of the TLP system equipped with a TLCD device was tested for various wave conditions in a wave basin and recordings were made using six load cells, two water-level probes, and four motion capture cameras. Six load cells measured the tension in newtons in each of the mooring lines. The load cells were Tedea–Huntleigh stainless steel single-ended bending beam load cells with a maximum load of approximately 50 N and were bolted to the gravity base (figure 1*b*). 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 water-level probes measured water surface elevations (millimetres) during testing. In order to measure the motions of the TLP, four reflective markers were attached to the corners of the hexagonal base (figure 1*a*). The instantaneous positions of the markers were monitored by the Qualisys 3-Series Oqus marker-tracking cameras with a sampling frequency of 32 Hz. The load cells and wave probes were triggered by National Instruments LabVIEW 2011 v. 11.0 software. The Qualisys marker-tracking system was time synchronized using LabVIEW.

(c) Experimental procedure

The model testing was carried out in a wave basin equipped with 40 flap-type paddles capable of generating sinusoidal wave profiles as well as two- and three-dimensional wave spectra. The still water depth is constant at 1.0 m. The TLP was tested for JONSWAP spectra with wave period 2.4 s, and Froude-scaled wave amplitudes, Hs, for 0.015, 0.02, 0.025, 0.03 and 0.035 m. The test schedule is shown in the electronic supplementary material, appendix A. A scaled mass was attached to the top of the mast to represent the loading of a wind turbine nacelle in no wind conditions. The TLP was fitted with MTLCDs and four different set-ups of the damping device were tested as indicated in table 2 for active and inactive conditions of the damper. The effects of reflected waves at the boundaries of the basin were removed by absorbing barriers and an inbuilt active absorption system in the wave flaps.

(d) Numerical analysis

In order to provide a basis for the experiments, numerical modelling of a TLP with a TLCD and MTLCDs was performed based on the work of Gao *et al.* [21] and Farshidianfar *et al.* [24], respectively. The response of the structure with a TLCD with different densities of working fluids as multiples of density of water was investigated in these simulations. The coding of the observed single and multiple TLCD cases on the TLP excited by the random force was done using Matlab [25]. In the first part of the numerical simulations, the changes in responses of the system were due to the changes in the mass of the damper, which was simulated by using different fluids with different density values and keeping all other parameters of the damper constant. Frequency responses were found for various values of density of the damping liquid/density of the water (m_{d}^{*}), varying from 2 to 6. Responses in the frequency domain were compared with responses which were obtained without the use of TLCD dampers. In the second part of the analysis, the time history responses of the structure were obtained by using random forcing obtained from the Pierson–Moskowitz spectrum with $U_{15.4} = 20\,\mathrm{m\,s^{-1}}$ and employing the following equation with $\alpha = 0.0081$, $\beta = 0.74$ and $\omega_0 = g/U_{15.4}$:

$$s(\omega) = \frac{\alpha g^2}{\omega^5}\mathrm{e}\left(-\beta\left(\frac{\omega_0}{\omega}\right)^4\right). \tag{2.1}$$

Numerical analysis of the results obtained from the experiments was carried out using the DVV [26] method. DVV is employed as a statistical marker to track structural changes in the system using only the dynamic responses of the platform and due to the presence of various designs of MTLCDs. DVV is based on a surrogate data methodology, elaborated in detail by Schreiber & Schmitz [27], for detecting the determinism and nonlinearity in a time series. The DVV method is explained and further elaborated and tested in Gautama *et al.* [28–30] and Mandic *et al.* [31]. A separate paper in this Theme Issue tests DVV for floating platforms and the potential of its use for tracking changes in structural properties is identified there [32]. Advantages of using this method relate to the facts that it does not require any prior knowledge about the system or the excitation, it is robust to the presence of noise, it is straightforward to interpret and typically exhibits improved performance over other traditionally available methods [30]. Numerical analyses were performed using the DVV toolbox [33]. The output of the method is one number for each response signal recorded, shown by the root mean square error (RMSE), and represents the degree of nonlinearity of the response [30]. In all DVV analyses the following parameters were kept constant: embedding dimension $m=3$, time lag $\tau=1$, maximal span parameter $n_d=2$, number of standardized distances for which target variances are computed $N_{tv}=50$, number of surrogates considered $N_{tv}=50$ and the number of reference DVs considered $N_{sub}=200$. Discussions related to the choice of these parameters and computation of DVV have already been already reported by Jaksic *et al.* [32,34].

3. Results and discussion

The TLP was excited by a wave spectrum of single peak frequency for 5 min in each test during which time the responses of the various load cells reached stable and repeatable peaks. The results of this experimental work along with the numerical modelling results and example of DVV analysis are presented in figure 2. An example of the raw data is given in the electronic supplementary material, appendix B.

The comparison of the surge energy measured by the yellow load cell when the system is damped by MTLCD3 is shown in figure 2*a*. The figure shows the comparison between two different sea states, when Hs is 15 and 35 mm, respectively, for conditions when the damper is inactive (closed) and active (open). The results show that the surge energy decreases when a TLCD is installed on the structure and this is in agreement with Lee *et al.* [8]. A comparison related to the maximum surge displacement is shown in figure 2*b*. The greatest reduction in maximum surge displacement is achieved (10–16%) for MTLCD2 for active dampers. The results are extremely consistent across all wave heights for MTLCD2 and MTLCD3, with some variance for MTLCD1 (2% increase—10% reductions). It should be noted that in the lower wave heights the thrust load is dominating, resulting in the variance between results with and without thrust applied. In the larger wave heights, wave loading is dominating, resulting in agreement between results. Figure 2*c* shows the results of the mooring tension comparison of representative (yellow) load cell measurements. The MTLCD2 design again shows the most promising results, and these results are extremely consistent over the range of wave heights tested.

The numerical modelling of the effect of MTLCDs on the TLP is performed in two parts. In the first part, the wave frequency (forcing frequency) is varied from 0 to 5 rad s^{-1}, where the maximum response is found. This was done for different working fluid densities and for each combination of dampers. The frequency response analysis for the MTLCD1 design shows that changing the density of the operating fluid does not significantly impact the structure response. For the MTLCD2 design, responses with density ratios of 1, 2 and 3 are almost the same. Beyond this, the dominant reduction in the dynamic response is only with density ratio 5, which may not be practical for implementation. Similar results are obtained for the MTLCD3 design. The results for numerical simulations of the MTLCD1 and MTLCD3 designs are not presented here as they only show this response comparison with water as the operating fluid. For illustration, figure 2*d* shows the maximum response plotted against the forcing frequency for the MTLCD2 design. The reduction in responses decreases as m_d^* increases up to 4 and then it increases. The minimum dynamic response is observed when m_d^* is between 3 and 4. In the second part of the numerical simulations, the dynamic responses to a random forcing are observed and the responses for each combination of MTLCDs with water as the working fluid are investigated. The forcing function was obtained using equation (2.1). It is observed that the damping rate is low in multiple TLCDs as compared with a single TLCD. It will take longer for the TLP with MTLCDs to come to rest after a random forcing than the TLP with a single TLCD. The decrease in the response frequency owing to the presence of a damper is shown in figure 2*e*. The frequency reduction is up to five times when MTLCDs are active.

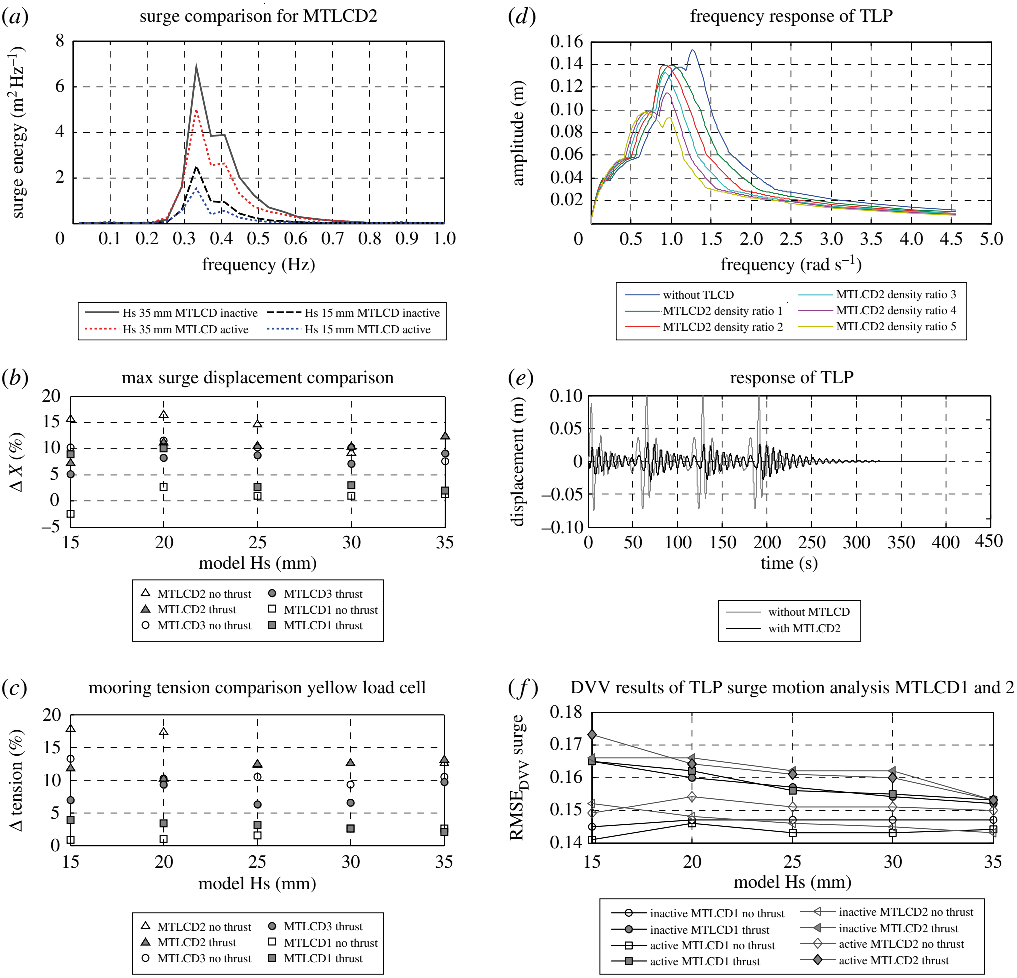

Figure 2. (*a*) Yellow load cell: frequency versus surge energy for the active and inactive MTLCD2 case for Hs = 15 and 35 mm. (*b*) Maximum surge displacement comparison and (*c*) mooring tension comparison for the yellow load cell. Numerical modelling: (*d*) frequency response of the TLP without a TLCD and with MTLCD2 for different fluid density ratios; (*e*) frequency response comparison of the TLP with MTLCD2 and without MTLCD and (*f*) DVV results of the surge motion analysis for the TLP with MTLCD1 and MTLCD2. (Online version in colour.)

The results of DVV analysis of the surge motion of the TLP are shown in figure 2*f*. The results show that the RMSE for the platform motion when the thrust is present decreases as the Hs increases. There is almost no difference in the degree of nonlinearity of the surge motions of the platform with active and inactive MTLCDs when thrust loading is present. Similarly, the platform with no thrust loading has an almost constant nonlinearity degree of response regardless of the wave height. This is in the agreement with the earlier findings that the TLP with MTLCD1 has high pretension and is stiff in lower wave conditions. On the other hand, when there is no thrust loading the TLP surge response nonlinearity is lowered when the MTLCDs are active.

4. Conclusion

This paper has investigated, by both numerical modelling and experimental testing methods, the effectiveness of MTLCDs for reducing motions in TLP-type offshore floating wind platforms. The physical model testing used simulated ocean wave spectra and showed that MTLCDs can be used to reduce the dynamic responses of the TLP. Furthermore, the results also indicate the positive effect of MTLCDs on tensile forces experienced by mooring lines. The numerical modelling presented confirmed these findings. The work undertaken highlights 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 indicate that, to achieve an optimal arrangement for the control of dynamic responses of TLPs, a significant range of adjustment is required to be carried out frequently over the lifespan of a structure. However, if the sea state spectra are known for intended operational conditions, an approximate tuning can result in mitigation of dynamic responses that are non-optimal but adequately close to the optimal mitigation for engineering purposes. The numerical modelling shows that there may be benefits in using MTLCDs over using one TLCD. Finally, the use of DVV in monitoring different structural conditions highlights the potential of developing output-only statistical markers monitoring dynamic behavioural changes in these devices.

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