Tuned Liquid Column Damper based Reduction of Dynamic Responses of Scaled Offshore Platforms in Different Ocean Wave Basins

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Abstract. Control of dynamic responses of renewable energy device platforms is important for their performance, safe operation and efficiency over their lifetime under regular and extreme wave conditions. Tuned Liquid Column Dampers (TLCDs) have been recently considered as a viable passive control mechanism in this regard but limited information is available in relation to their experimental performance. This paper compares scaled experiments conducted in two different ocean wave basins where floating offshore platforms were retrofitted with multiple TLCDs (MTLCDs). Performance of such MTLCDs in these scaled ocean wave basins are evaluated and compared considering control of dynamic responses for a specific objective. This paper shows the potential of MTLCDs to reduce motions in offshore platforms for different designs and platforms of MTLCDs and provides a comparison of the levels of reduction of dynamic responses achieved. The performance of MTLCDs in different wave basins create an experimental evidence base behind the potential use of such solutions, the objectives of such use and highlight related challenges and limitations.

1. Introduction

Offshore wind developments offer many benefits, such as increased wind speeds as they are placed at further distances from the shore, less turbulence and less opposition from the public, as is seen toward onshore turbines [1]. In deep water, floating platforms must be employed to harness wind energy in an economically viable way [2], and with floating platforms comes a greater need for solutions to ensure more stable operating conditions [3]. A platform with a higher tolerance of high sea states, and a lower wave sensitivity will likely be a more economically favourable design [4]. Damper
Technologies have been employed in civil infrastructure as a means of structural control [5]. They have been applied to the stabilising of tall buildings [6] and as method of earthquake protection [7]. Technologies include tuned-mass dampers, fluid-viscous dampers and tuned liquid column dampers (TLCDs). More recently, these systems have been applied to offshore platforms; spring dampers [8], buoyant mass dampers [9], tuned liquid dampers [10,11], and tuned-mass dampers [12,13] have all been investigated both numerically and experimentally, to varying success. Tuned Liquid Column Dampers (TLCDs) are structural control devices which use the energy dissipated by the movement of water in liquid columns, typically U-shaped, of tuned lengths which dissipate excitations within the structure. They are a low-cost, low-maintenance passive damping solution, which can be easily installed. Parameters of TLCDs affecting their performance have been investigated [14], and systems can be design to meet specific requirements. The application of TLCDs to offshore systems has been well investigated numerically [15, 16, 17, 18] but, though examples exist [19], experimental comparisons in this topic are not adequately well-represented in literature. Dynamic responses and related control can be used for monitoring through markers [20].

In this paper, a recent experimental regime of a new MTLCD design retrofitted to a model of a floating wind platform is presented. The retrofitted platform was tested under various wave conditions in a deep ocean wave basin, while displacement data was recorded, from which acceleration data can be derived. These results are compared with results from previous testing of a different model, in a different ocean wave basin. It is hoped that this paper successfully demonstrates that results obtained in these two different cases, where the tank, the structure and the parameters of the TLCD all differed, are still comparable in scale and offer a benchmark for scaled tank testing of such systems.

2. Experimental Details
Experiments were carried out in the newly commission ocean wave basin in the Lir National Ocean Test Facility in Cork, on a scaled semi-submersible structure, designed by Iberdrola, which is part of the European Union EU FP7 LEANWIND project. TLCDs were retrofitted to the device, their dimensions tuned to reduce hub height accelerations for a set of wave conditions.

![Figure 1. Semisubmersible floating wind platform model, fitted with TLCDs, on site at the Lir National Ocean Test Facility, prior to wave testing](image)
2.1. Scaled Model
The platform (Figure 1) is a floating, semi-submersible hollow steel structure, moored by 3 cable-spring systems designed to represent the behaviour of a catenary line at full scale. The bow leg holds a mast on which a fan, used to simulate a turbine at model scale, can be mounted. During testing, a scaled mass was added to the top of the mast, to simulate the weight of a turbine, and so the effect of aerodynamic rotor thrust was not examined during testing.

2.2. Wave tank
The wave tank is 35m long and 12m wide, with a moveable floor which can go up to 3m deep, seen in figure 2 during testing. The platform was subjected to 1:36 Froude scaled waves, and the Bretschneider spectrum was used to simulate ocean conditions. The wave profiles used are defined by significant wave height ($H_s$) and wave period ($T_p$), and the time series of the waves are generated by from the frequency domain representation of wave spectra.

![Figure 2. The wave tank in operation at the Lir facility.](image)

The wave cases chosen to test the platform were Bretschneider Spectrum waves, of 2.5m significant wave height ($H_s$) and periods ($T_p$) of 6, 9, 11, 12, 15 and 17 seconds respectively. A previous paper by Jaksic et al. [21], showed results with good consistency across different wave heights, so in this paper the focus was on different wave periods and the effect they might have on the effectiveness of a TLCD’s tuning to the wave frequency. The wave cases were chosen to cover a wide range of wave frequencies, each for a period of 14 minutes which allowed time to establish the wave, a 10-minute period of continuous steady data acquisition, and time at the end for the oscillations to settle. The wave cases were each run for the three different platform arrangements; no TLCD (to create baseline from which change could be measured), ‘TLCD1’ in active state (valve open and water free to move), and ‘TLCD2’, also in its active state.

2.3. Instrumentation
The choice of sensors for wave basin testing has been previously investigated [22], and a high-resolution camera tracking system is employed here. The Qualisys motion capture system, with 4 Oqus3 cameras, was used to record the position of the platform by tracking 4 markers attached to different parts of the platform. This positional data was used to derive acceleration data at hub height.
2.4. TLCD Design

The peak frequency of the set of sea states selected for this analysis was between .08 and .13 Hz. This range was chosen as the frequency to which to tune the TLCD. Comprehensive equations summarising their behaviour were presented by Yalla & Kareem [23], but the key governing design decision taken is based on finding the length of liquid column \( L_d \) obtained from the frequency to which TLCD is tuned \( \omega_{\text{TLCD}} \).

Using this equation, the required length of water column was calculated for the frequency being designed to. Other optimum parameters for TLCDs are investigated by Yalla & Kareem [23], and some of their findings instructed the design featured here. The horizontal to vertical length ratio was kept at a minimum, within practical boundary conditions.

Mass ratios were between 1 and 5%. Two TLCD combinations were designed and tested. The first, referred to as ‘TLCD1’, seen in figure 3 (a), consists of two symmetrically mounted TLCDs both tuned to the peak input frequency by liquid column lengths of 1.1m. The TLCDs weighed 1.8% of the total platform mass. Ballast was removed from the front leg of the platform to re-level the platform, and the difference in draft, and the change in mooring tension that would result, was accounted for by adjusting the movable tank floor accordingly.

Figure 3. (a) ‘TLCD1’ configuration, two 1.1m liquid columns. (b) ‘TLCD2’ configuration, four liquid columns of different lengths.

The second, ‘TLCD2’, shown in figure 3 (b), consists of four TLCDs, each of different liquid column lengths (1.1m, 1.2m, 1.3m and 1.4m, respectively), which corresponded to values bounding the peak frequency value, but covering a greater range of frequency values. The TLCDs in this case weighed 3% of the total platform mass. Additional ballast was removed and the floor was lowered to account for further draft change. The TLCDs were constructed from clear PVC piping, of 25mm and 32mm external diameters. A valve was added to each as a method to control whether the device was ‘active’ (valve open, water free to move) or ‘inactive’ (valve closed). They were mounted on custom made steel brackets, which suspended them above the wave surface, to avoid extra drag being introduced to the system.

3. Results and Discussion

As top-of-mast accelerations are often a design limit state criterion, both raw displacement data at the top of the mast and acceleration data derived from this were analysed. Using this data, comparisons were made between different wave cases and different platform configurations, shown in figure 6. Figure 4 (a) shows the comparison of mean surge displacement, and shows a small (approx. 1%) but consistent reduction in mean displacement for both active MTLCD systems, with ‘TLCD2’ being the most effective. A similar situation is observed in figure 4 (b), where a 1.9% reduction in peak displacement was achieved. The results are reasonably consistent across all wave periods.
Figure 4. (a) Reduction in mean displacement in the surge direction, (b) reduction in maximum displacement in surge direction, (c) reduction in mean acceleration, (d) reduction in maximum acceleration, all for top of mast.

Figure 4(c) shows a significant percentage reduction in mean acceleration at the top of the tower due to the addition of the MTLCD systems, with ‘TLCD2’ proving again to be most effective with a maximum of 13% reduction achieved. The peak acceleration sees a maximum of 16% reduction, seen in figure 4(d), and once again ‘TLCD2’ is consistently the most effective across all wave periods. Of great interest during this testing was the reduction of hub height accelerations, a given value of which is often an important limit state criterion in the design of such structures.

A Weibull probability density fit (figure 5) was used on the data as a means of assessing the change in data distribution. For the TLCD1 and TLCD2 systems, respectively, the peak of the distribution is closer to the y-axis, making the data more right skewed towards lower acceleration values. A ‘flattening’ of the tail shows a reduction in the probability of the occurrence of maxima.
Figure 5. Weibull probability density function comparison.

The work by Jaksic et al. [21] assessed reductions due to three different MTLCD designs when retrofitted to a tension leg platform (TLP) at 1:50, and testing was carried out in a different ocean wave basin.

Figure 6. Comparison of maximum surge displacement for (a) TLP model (b) semisubmersible model.

Figure 6 (a) shows a reduction in surge displacement of up to 16% for TLCD systems of 15, 20 and 30% mass ratios. The current work resulted in maximum displacement reduction of 1.9% (figure 6 (b)), however this was for devices of 1.8 and 3% mass ratios. The differences in testing parameters, such as the TLP platform in the 1m deep wave basin compared to the semisubmersible catenary-moored platform in the 3m deep basin, are to be considered even in this dimensionless side-by-side comparison.
4. Conclusions
This work details the retrofitting a system of multiple tuned liquid column dampers to a scaled semisubmersible floating wind platform model for testing in an ocean wave basin. Investigation into reduction of accelerations at the top of the platform’s mast is an important objective for these tests. The installation of TLCDs had a significant, positive effect on reducing hub height accelerations of the mast. TLCD2 was the most effective configuration, the 4 different lengths of water column, designed to control for a range of frequencies, having the desired effect. Results showed the favourable effect of the TLCD on the platform’s displacement was small (approx. 1%). Reductions of up to 16% were achieved in maximum acceleration values, and an average of 8% and 11% reduction in mean acceleration values for TLCD1 and TLCD2, respectively. These results were consistent across input wave periods, and TLCD2 was the more effective design in all cases. The load cases were chosen to test the peak frequencies to which the device was designed, and results show that both designs were effective in the design objective of damping the motions these waves induced. The results are comparable to previous scaled tests on a different platform and basin, and this implies a level of repeatability is achievable across different wave tanks in terms of demonstration on control of off accelerations using TLCDs at a scaled model level.

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References
[1] Henderson AR, Morgan C, Smith B, Sørensen HC, Barthelme RJ, and Boomsans B, “Offshore wind energy in europe - A review of the state-of-the-art,” Wind Energy, vol. 6, no. 1, pp. 35–52, 2003.
[2] Musial W, Butterfield S, and Ram B, “Energy From Offshore Wind,” Offshore Technol. Conf., pp. 1–11, 2013.
[3] European Wind Energy Association, Deep water, July. 2013.
[4] Butterfield S, Musial W, Jonkman J, and Sclavounos PP, “Engineering Challenges for Floating Offshore Wind Turbines” Copenhagen Offshore Wind Conference, Copenhagen, Denmark, 2005.
[5] Housner GW, Bergman LA, Caughey TK, and Chassiakos AG, “Structural control: past, present, and future,” J. Eng. Mech., vol. 123, no. 9, pp. 897–971, 1997.
[6] Diana G, Resta F, Sabato D, and Tomasini G, “Development of a methodology for damping of tall buildings motion using TLCD devices,” Wind Struct., vol. 17, no. 6, pp. 629–646, 2013.
[7] Gowda KK and Kiran KK, “Earthquake resistance of structures using dampers - a review,” Int. J. Adv. Struct. Geotech. Eng., vol. 2, no. 1, pp. 31–35, 2013.
[8] Wright C, O’Sullivan K, Murphy J, and Pakrashi V, “Experimental Comparison of Dynamic Responses of a Tension Moored Floating Wind Turbine Platform with and without Spring Dampers,” J. Phys. Conf. Ser., vol. 628, p. 12056, 2015.
[9] Moharrami M and Tootkaboni M, “Reducing response of offshore platforms to wave loads using hydrodynamic buoyant mass dampers,” Eng. Struct., vol. 81, pp. 162–174, Dec. 2014.
[10] Jin Q, Li X, Sun N, Zhou J, and Guan J, “Experimental and numerical study on tuned liquid dampers for controlling earthquake response of jacket offshore platform,” Mar. Struct., vol. 20, no. 4, pp. 238–254, 2007.
[11] Jaksic V, Wright C, Chanayil A, Ali SF, and Murphy J, “Performance of a Single Liquid Column Damper for the Control of Dynamic Responses of a Tension Leg Platform,” J. Phys., vol. 12058, pp. 1–8, 2015.
[12] Wu Q, Zhao X, and Zheng R, “Experimental Study on a Tuned-Mass Damper of Offshore for
Vibration Reduction,” J. Phys. Conf. Ser., vol. 744, pp. 2–10, 2016.
[13] Stewart GM and Lackner MA, “The impact of passive tuned mass dampers and wind–wave misalignment on offshore wind turbine loads,” Eng. Struct., vol. 73, pp. 54–61, Aug. 2014.
[14] Gao H, Kwok KCS, and Samali B, “Optimization of tuned liquid column dampers,” Eng. Struct., vol. 19, no. 6, pp. 476–486, 1997.
[15] Colwell S and Basu B, “Tuned liquid column dampers in offshore wind turbines for structural control,” Eng. Struct., vol. 31, no. 2, pp. 358–368, 2009.
[16] Coudurier C, Lepreux O, and Petit N, “Passive and semi-active control of an offshore floating wind turbine using a tuned liquid column damper,” IFAC-PapersOnLine, vol. 28, no. 16, pp. 241–247, 2015.
[17] Chatterjee T and Chakraborty S, “Vibration mitigation of structures subjected to random wave forces by liquid column dampers,” Ocean Eng., vol. 87, pp. 151–161, 2014.
[18] Roderick C, “Vibration Reduction of Offshore Wind Turbines Using Tuned Liquid Column Dampers,” Masters Thesis, 2012.
[19] Jaksic V, Wright C, Mandic DP, Murphy J, and Pakrashi V, “A Delay Vector Variance based Marker for an Output-Only Assessment of Structural Changes in Tension Leg Platforms,” J. Phys. Conf. Ser., vol. 628, no. 1, p. 12059, 2015.
[20] Pakrashi V, O’Shea R, Jaksic V, and Murphy J, “The Hurst Exponent as an Indicator of the Behaviour of a Model Monopile in an Ocean Wave Testing Basin,” J. Phys. Conf. Ser., vol. 628, no. 1, p. 12057, 2015.
[21] Jaksic V, Wright CS, Murphy J, Afeef C, Ali SF, Mandic DP, and Pakrashi V, “Dynamic response mitigation of floating wind turbine platforms using tuned liquid column dampers,” Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., vol. 373, no. 2035, pp. 20140079–20140079, 2015.
[22] O’Donnell D, Srbinovsky B, Murphy J, Popovici E, and Pakrashi V, “Sensor Measurement Strategies for Monitoring Offshore Wind and Wave Energy Devices,” J. Phys. Conf. Ser., vol. 628, no. 1, p. 12117, 2015.
[23] Yalla SK and Kareem A, “Optimum Absorber Parameters for Tuned Liquid Column Dampers,” J. Struct. Eng., vol. 126, no. 10, p. 1187, 2000.