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A Delay Vector Variance based Marker for an Output-Only Assessment of Structural Changes in Tension Leg Platforms

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Abstract. Although aspects of power generation of many offshore renewable devices are well understood, their dynamic responses under high wind and wave conditions are still to be investigated to a great detail. Output only statistical markers are important for these offshore devices, since access to the device is limited and information about the exposure conditions and the true behaviour of the devices are generally partial, limited, and vague or even absent. The markers can summarise and characterise the behaviour of these devices from their dynamic response available as time series data. The behaviour may be linear or nonlinear and consequently a marker that can track the changes in structural situations can be quite important. These markers can then be helpful in assessing the current condition of the structure and can indicate possible intervention, monitoring or assessment. This paper considers a Delay Vector Variance based marker for changes in a tension leg platform tested in an ocean wave basin for structural changes brought about by single column dampers. The approach is based on dynamic outputs of the device alone and is based on the estimation of the nonlinearity of the output signal. The advantages of the selected marker and its response with changing structural properties are discussed. The marker is observed to be important for monitoring the as-deployed structural condition and is sensitive to changes in such conditions. Influence of exposure conditions of wave loading is also discussed in this study based only on experimental data.

1. Introduction

The wind industry is moving toward bigger turbines, larger blades, taller towers, and into deeper ocean waters in order to use the potential of the strong winds. The studies show that the deep offshore designs, floating foundations, are competitive in terms of the levelised cost of energy (LCOE) with bottom fixed foundations in water exceeding 50m in depth [1-3].

However, with moving offshore structures into deeper water the maintenance and monitoring of the structures are becoming critical problem [4]. Further offshore structures supporting energy devices are exposed to often unpredictable and extreme weather conditions, which could influence their performance, stability during maintenance and operations, and overall cost of the offshore device floater [5-7]. Therefore, continuous observation of a floating supporting structure for offshore devices exposed to the highly variable met-ocean conditions is one of the ways to monitor performance and

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health of the structure [8, 9]. Hence, the remote monitoring of the complex dynamics of the floaters [10, 11] caused by the wind, wave, and wind-wave loading combined with statistical analysis of its responses can be used for structural health monitoring (SHM). The markers identified through the statistical analysis of the structure output only signal can help in the pattern forming recognition system of the behavior changes of the offshore structures. However, in the early stage of development, the quantitative estimates of the stochastic dynamic responses and assessment of the corresponding markers are only possible using scaled testing in laboratory setting [6, 12]. Further, measurement of the dynamic responses of scaled floating foundation model in wave tank is the first step in assessment and understanding of structural dynamic responses, since the prototype in sea testing can be difficult and expensive during at the design stage [13, 14].

This study presents the results of the wave tank testing of a 1:50 Froude scaled Tension Leg Platform (TLP) supporting wind turbine structure. The platform is equipped with the Tuned Liquid Colum Damper (TLCD) which is used to mitigate horizontal motions of the platform [12, 15]. The design of the TLCD is based on the Yalla and Kareem [16] study. Therefore, the overall length of the water column is calculated by equalising irregular wave frequency with water column frequency.

Structural response of the floater exposed to sea states characterized by the Bretschneider (BS) and Joint North Sea Wave Observation Project – JONSWAP (JS) spectra was monitored for two different damper–TLP mass ratio (μ = 5% and 10%) and for three different experimental setups of the damper (when TLCD active /open, inactive/closed, and no TLCD case). The dynamic response was recorded using load cells and camera based motion recognition system. The structural behaviour of the platform was observed for when there is and there is no thrust loading on the mast representing wind effects, for various wave periods and amplitudes, in order to establish the correlation between imposed changes and the selected statistical marker.

This study examines the possibility of employing the Delay Vector Variance (DVV) method for analysis of output only signal, i.e. responses of the TLP, in order to investigate this marker for assessing change in variation of structural parameters brought about by intervention in the form of control [8]. DVV method is used in quantification of linearity or nonlinearity of the structural system response signals as indicator of the nature of the structural behaviour due to changes in the excitation force and TLCD design. DVV method was previously used successfully in different scientific disciplines where outputs of the system response were analyzed for the change in its linearity due to the variation of the system parameters [8, 17-21]. The change in the degree of nonlinearity in the signal is characterized by a Root Mean Square Error, (RMSE) as a marker [22]. The study uses obtained RMSE to discuss TLP tendons behavior changes caused by different sea states and two TLCD designs. The results of this study are encouraging and form the basis in further investigation of TLCD application in offshore wind energy substructure behaviour.

2. Experimentation

2.1. TLP Model equipped with Tuned Liquid Column Damper (TLCD)

The TLP platform tested is a truss structure with hexagonal floating platform. The platform is connected to the gravity base, located at the bottom of an ocean wave basin, with the six mooring tethers. The floating platform consist of the buoyancy ring and the upper structure. The buoyancy ring structure is made of six 90mm diameter Polyvinyl chloride (PVC) pipes, joined to the central column by six 40mm diameter PVC pipes. The upper structure, located above the buoyancy ring, is built 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 is not submerged. The central column is fabricated from 160mm diameter PVC pipe and provides sufficient buoyancy to counterbalance the tower and nacelle weights. The additional buoyancy force is passed on the six mooring lines made of 2mm diameter stainless steel wire which are in tension at all times. The weight of the TLP is 16.8kg. The wind turbine tower is made of 50mm diameter 1.15m high PVC pipe (0.8kg). The thrust load at the top of the tower is 2.2kg.

A U-shape TLCD device, designed following Yalla and Kareem [16], is attached to the TLP upper structure at the level of the center of the gravity (CG). TLCD is tuned to the average frequency of the longest Bredschneider waves that the basin can generate (0.59Hz). The TLP response was monitored using two TLCD designs. The mass ratio, μ (mass of liquid in the tube, m_d, vs. mass of the primary system, *Ms*) was in the first 5%, and in the second case 10%, having pipe diameter 30mm and 40mm, respectively. The horizontal part of the TLCD was 1m long while the vertical part was 0.6m long (filled with water up to 0.2m) to allow for water sloshing and prevent its loss. Figure 1a shows the experimental set up of TLP.

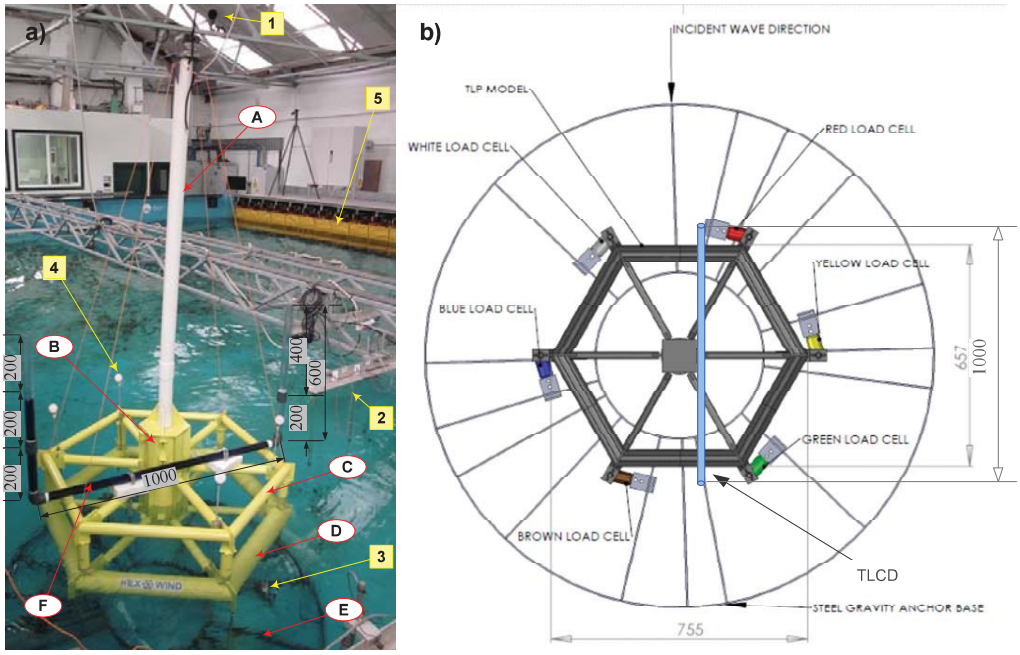

Figure 1: a) 1:50 Scale Model of Truss type TLP Platform experimental setup: (A) mast, (B) central column, (C) upper structure, (D) buoyancy ring, (E) gravity base, and (F) TLCD. The locations of devices used: (1) motion camera, (2) wave probes, (3) load cells, (4) reflective motion markers, and (5) 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.

2.2. Instrumentation

The response of the TLP structure and the effects of TLCD device on its performance, while exposed to the known characteristic waves for a period of time, was recorded in the laboratory environment using six load cells, four motion capture cameras, and two water level probes. Stainless steel single ended bending beam load cells (Tedea-Huntleigh) measured the tension in mooring lines in Newton (maximum load ~ 50N). The gravity base with load cell arrangement and position of TLCD in relation to the incident wave direction is shown in Figure 1b. Each load cell was given a name during the testing, i.e. White (Bow Port), Red (Bow Starboard), Blue (Amidships Port), Yellow (Amidships Starboard), Brown (Stern Port), and Green (Stern Starboard). Two water level probes were measuring the height of water in mm during testing and could therefore measure the profile of the waves generated in the wave basin which the model was exposed to. Four reflective markers were attached to the corners of the hexagonal base for assisting in measuring the motions of the TLP during the experiment (Figure 1a). Qualisys 3-Series Oqus Marker Tracking Cameras, with 32Hz sampling frequency, were used to determine the momentary positions of the markers. 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 using Labview.

2.3. Experimental strategy

The TLP model was tested in an ocean wave basin equipped with 40 flap type paddles able of generating sinusoidal wave profiles as well as 2 and 3-D wave spectra. The still water depth is constant at 1.0m. The TLP was tested for BS and JS spectra, wave period, T_p= 2.4sec, wave frequency, f_p=0.42Hz, and Froude scaled (model) wave amplitudes, Hs_m, 0.05 and 0.075m (H_s = 2.5 and 3.75m respectively), with and without thrust loading. Additionally, TLP platform was tested for: BS spectra when T_p=1.2 and 3.6s corresponding to f_p=0.83 and 0.28Hz, respectively, for wave amplitude Hs_m, 0.05m without thrust loading and BS spectra when T_p=2.4s, f_p=0.42Hz for wave amplitude Hs_m, 0.1m (H_s = 5m) without thrust loading. A mass (0.8kg) was attached to the top of the mast to act as the loading of a wind turbine nacelle in no wind conditions. The TLP was provided with the TLCD and four different setups of the damping device were tested, i.e. with μ = 5% and 10% mass ratio when active and inactive. Effects of reflected waves at the boundaries of the basin were removed by dissipating the energy in an immersed barrier made of randomly oriented, rigid objects.

3. Delay Vector Variance (DVV) Methodology

The load cell measurements were analysed using the Delay Vector Variance (DVV) method [23] in order to quantify the extent of nonlinearity of the structural system response to the variable sea conditions and to determine to what extent the nonlinearity of the response signal is linked to changes of the observed TLP system and its exposure to different forces. DVV method, based on surrogate data methodology [24], detects the determinism and nonlinearity in a time series. The explanation and testing of the DVV methodology is given in Mandic et al. [25] and Gautama et al. [26]. DVV was successfully employed as statistical marker to track the response changes due to the changes in the system using the output only signal in different research fields [18, 20-22, 27]. The potential of using DVV method to analyze and track changes in structural properties of the floating platform due to its exposure to different wave types is investigated in Jaksic et al. [8]. The advantages of the proposed method are related to the facts that it does not require any prior knowledge about the system or the excitation force, it is robust to the presence of noise, straight forward to interpret and typically has improved performance over traditionally used methods [20].

Numerical analyses were performed using the DVV Toolbox [27]. The output of the method is one number for each response signal recorded represented by the Root Mean Square Error (RMSE) and represents the degree of nonlinearity of the response [20]. Following DVV parameters were kept constant during analysis: the embedding dimension m=3, time lag τ= 1, the maximal span parameter is n_d=3, the number of standardized distances for which target variances are computed is N_{tv}=50, number of surrogates considered is N_s=50, and the number of reference DVs considered is N_{sub}=200. Discussions related to the choice of these parameters and computation of DVV is reported by Jaksic et al. [8].

DVV scatter diagram can be produced by performing DVV analysis on the original and a number of surrogate time series. If the surrogate time series yields DVV plots similar to the original time series, in which case the DVV scatter diagram coincides with the bisector line, then the original time series is considered to be linear. The deviation from the bisector line, quantified by an RMSE is an indicator of nonlinearity of the original time series [26]. As the degree of nonlinearity increases, the deviation from bisector line grows. The example of the load cell measurements recorded and DVV scattered plots obtained are given in Figure 2.

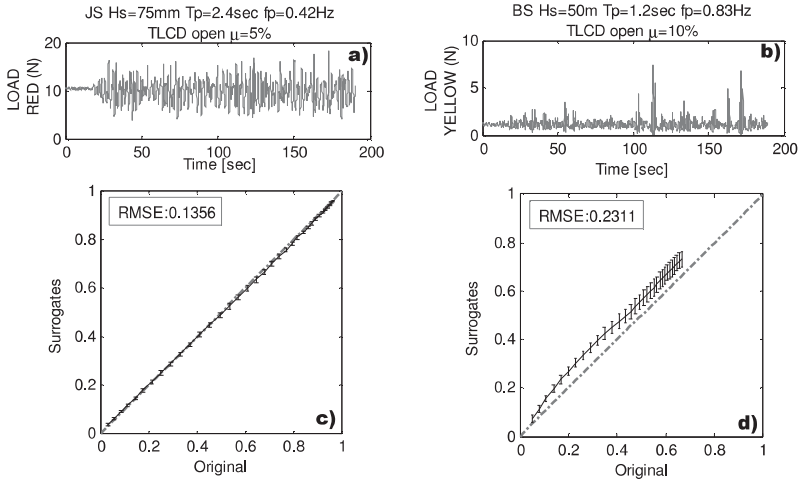

Figure 2: a) Red load cell measurements for TLP with no Thrust excited by JONSWAP waves Hs=75mm high, period Tp=2.4sec, and frequency fp=0.42Hz; b) Yellow load cell measurements for TLP with no Thrust excited by Bretschneider waves Hs=50mm high, period Tp=1.2sec, and frequency fp=0.83Hz; c) DVV scatter diagram corresponding to a) measurements, and d) DVV scatter diagram corresponding to b) measurements.

4. Results and Discussion

The TLP was excited by different waves for about three minute in each test. The total number of test performed is 42. The load cell measurements were recorded and DVV analysed. The degree of the nonlinearity (RMSE) of forces in tendons due to the changing wave characteristics, presence of two different TLCD designs, and thrust loading is estimated and compared.

Figure 3 shows results of DVV analysis when TLP is exposed to BS and JS waves (T_p=2.4s and f_p=0.42Hz). The presented results indicate that there is the change in the degree of linearity of recorded load cell measurements for both types of loading. When TLP with no TLCD is exposed to BS wave spectra the highest RMSE in loading is experienced by Blue and Yellow load cell. However the difference in RMSE (ΔRMSE) due to variation in wave heights is negligible being greatest for the Brown (ΔRMSE=0.006). For TLP exposed to BS with TLCD (μ=5%) installed, the RMSE graph becomes distorted in such way that the highest variation in degree of nonlinearity is recorded by White cell when TLCD is closed and Hs_m=100mm (Figure 3a). However, due to the presence of the damper active and inactive ΔRMSE is highest for Brown and Blue load cells. This could be due to the eccentricity in TLP loading caused by the TLCD location since ΔRMSE is lower for Red, Yellow, and Green load cells which are on the side where TLCD is installed. The results obtained for TLP exposed to BS when there is thrust loading show in general small reduction in RMSE (Figure 3b) in comparison with results observed for when there is no thrust loading (Figure 3a). However, it appears that when trust present level of nonlinearity in load cells measurements depend on the H_s rather than on the activity of the TLCD in such way that with increased H_s RMSE is reduced for all load cells but for Brown. However, this could be due to combined effect of the position of the TLCD and the thrust loading hanging in between Green and Brown cell from the top of the tower. Thus, when TLCD and thrust loading combined they become responsible for the distribution of the loading in the load cells causing different degree of the nonlinearity in the signal measured. Figure 3c shows the results of the TLP exposed to BS spectra for TLCD with μ=10%. In this case the variation in RMSE due to the different in Hs and TLCD two setups is greater than when TLCD μ=5% for all load cells. However, the highest variation ΔRMSE obtained on the White load cell measurements. The reason could be the change in the load cells pretension loading due to the heavier TLCD. The results of the TLP exposed to JS with varying Hs with closed and opened TLCD show that the difference in the level of

nonlinearity depends on wave height but also on the activity of TLCD (Figure 3d). When thrust loading introduced to the TLP system exposed to JS (Figure3e) the RMSE decrease in comparison with the cases without the thrust. Also it appears that the level of nonlinearity between load cells is distributed almost equally. However, the RMSE is higher for inactive TLCD being the highest for the tendons on the side of (below) the damper, i.e. Read, Yellow and Green. The web figure obtained for RMSE of TLP exposed to JS equipped with TLCD (μ=10%) has the same shape footprint as the one obtained for BS wave spectra (Figure 3f). However, RMSE is higher for JS than for BS, which proves that the degree of linearity depend on the types of waves as well as on the location of the TLCD.

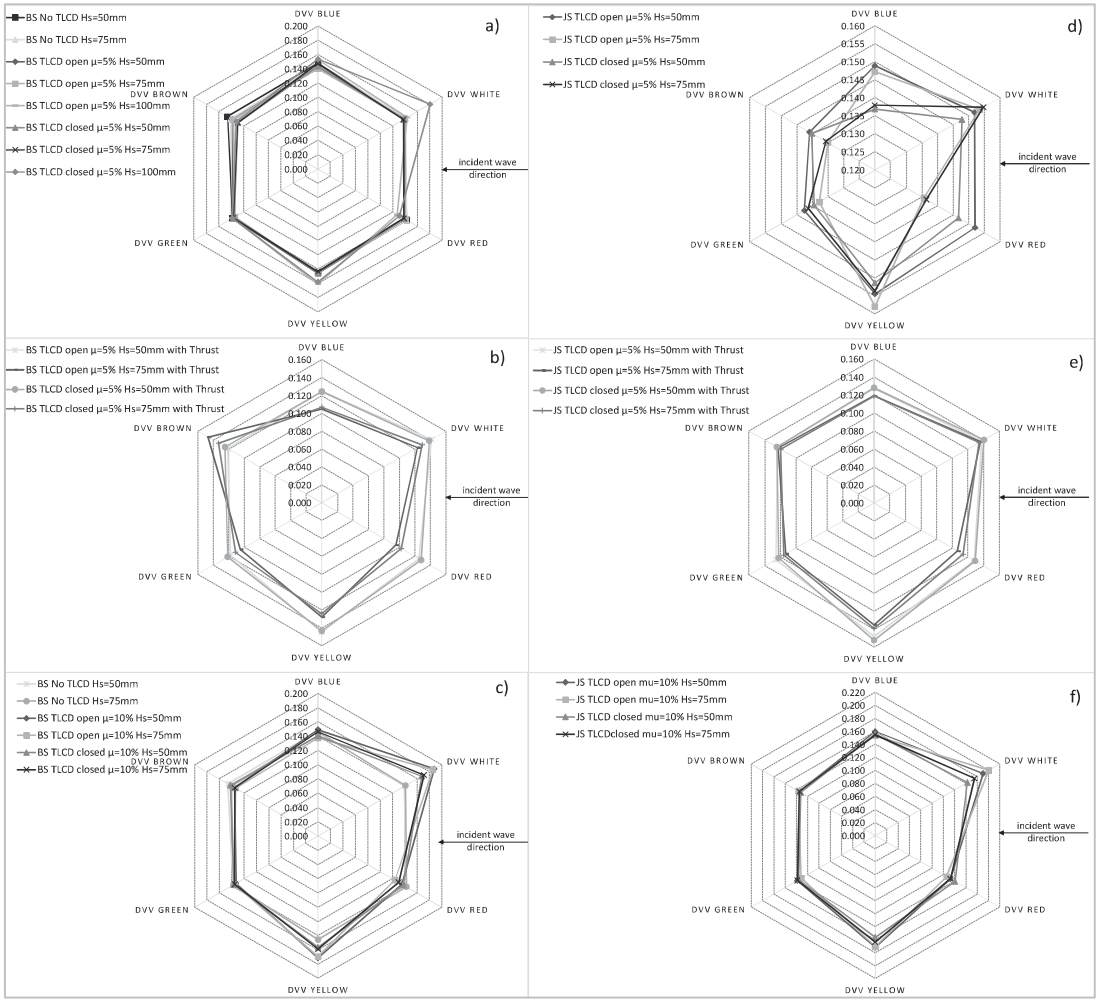

Figure 3: DVV analysis results (RMSE) for waves with Tp=2.4s and fp=0.42Hz a-c) Bretschneider spectra: a) for Hs_m= 50, 75, and 100mm without TLCD and with open and closed TLCD (μ=5%); b) for Hs_m= 50 and 75mm with open and closed TLCD (μ=5%), and with thrust loading; c) for Hs_m= 50, and 75mm without TLCD and with open and closed TLCD (μ=10%), and d-f) JONSWAP spectra: d) for Hs_m= 50 and 75mm with open and closed TLCD (μ=5%); e) for Hs_m= 50 and 75mm with open and closed TLCD (μ=5%), and with thrust loading; f) for Hs_m= 50, and 75mm with open and closed TLCD (μ=10%).

The trend in DVV results of tendon loading when TLP subjected to BS wave spectra of T_p=1.2, 2.4, and 3.6s, corresponding to f_p=0.83, 0.42, and 0.28Hz is shown in Figure 4. In majority observed

cases the degree of the nonlinearity of the load cell response is increasing with wave period increase (i.e. wave frequency decrease. The exceptions are the results for open TLCD (μ=10%) in case of Yellow, White, and to less extent Brown load cell and open TLCD (μ=5%) in case of White load cell for lower period / higher frequency waves. This also proves that the location of the TLCD contributes to the change in the system behavior. Further, it shows that the change in the damper–TLP mass ratio and the tuning of TLCD design are contributing the system change as well. This finding is in agreement with findings by Lee et al. [15] and Jaksic et al. [8].

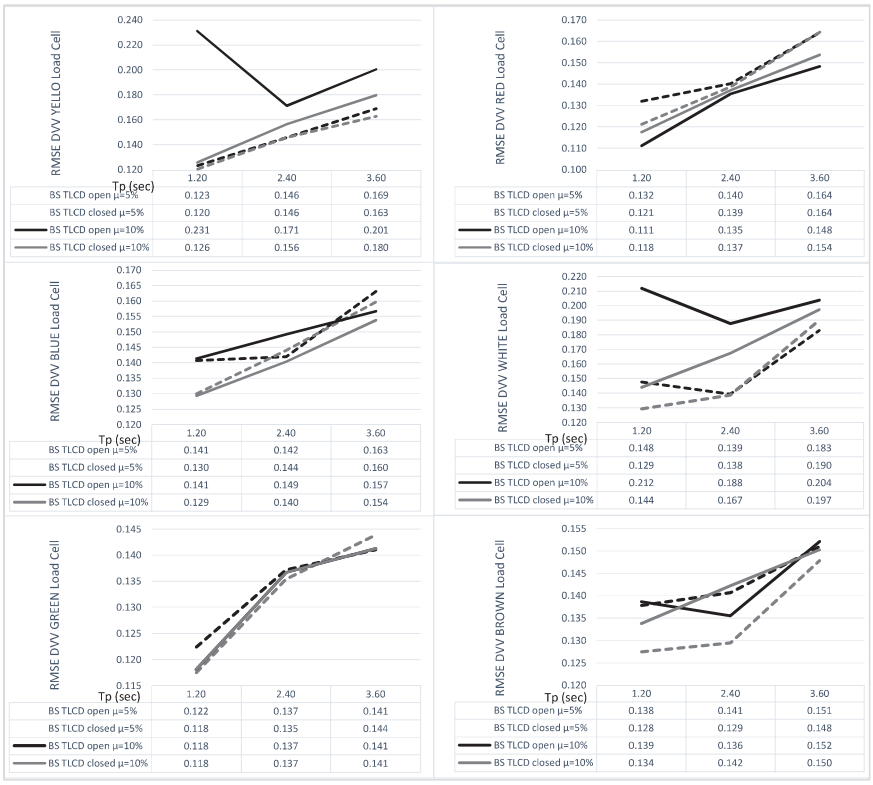

Figure 4: DVV analysis results (RMSE) for Bretschneider spectra waves in function of wave period Tp=1.2, 2.4, and 3.6s and frequency fp=0.83, 0.42, and 0.28Hzfor TLP with open and closed TLCD (μ=5% and 10%).

5. Conclusion

The Delay Vector Variance (DVV) method has been employed to characterize the behavior of the tendons of the scaled floating foundation model in the wave tank. The quantification of the change in degree of nonlinearity of the loadcell measurements as indicators of the nature of the structure and changes within are discussed. The results from different measurement suggests that the variability in estimated nonlinearity is observed to be representative of the different sea state condition and activities due to presence of the TLCD and the relationship of various components are also found. The analysis of the DVV results obtained from the variation in the sea states indicate that the level of the responses depend on the tendon locations in relation to the incident wave direction, but also depends the damper–TLP mass ratio (TLCD design) and its location, i.e. mass eccentricity relative to the TLP center of the gravity. The influential factor for the degree of nonlinearity is also thrust loading.

The DVV method in combination with online structural monitoring can be used for the fast and inexpensive structure assessment. Hence, the finding of the research can be the part of the early warning system for potential malfunctioning or structural failure which can in return minimize the

costs related to the operation and maintenance of the offshore (floating) structure. Additionally the evolution of the estimated nonlinearities of different components over time may serve as an output-only marker for the assessment of the structural health.

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