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Review on Mooring Lines Damping for Wave Energy Converter (WEC)

Adibah Fatihah Mohd Yusof,[a], J.Koto,[a,b,*] Nur Aireen Amran,[a], and C.L. Siow,[a]

[a)] *School of Mechanical Engineering,Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru*
[b)] *Ocean and Aerospace Research Institute,Indonesia*

*Corresponding author: jaswar.koto@gmail.com, jaswar@utm.my

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ABSTRACT

The WEC mooring system is needed to withstand the environmental loadings and to limit the excursion of the floating structure without affecting the power production efficiency. MDD type WEC is designed to have device resonant period match to mooring system at the wave frequency (WF). A coupled time domain analysis has to be used to analyze the influence of mooring line to the WEC motions. A literature review on the methods used to estimate the mooring line damping for WEC has been conducted. It is found that finite element method is can be used to model the nonlinearities of mooring line better than quasi-static method.

KEY WORDS: *Mooring Line Damping, Wave Energy Converter, Time Domain, Dynamic Analysis.*

NOMENCLATURE

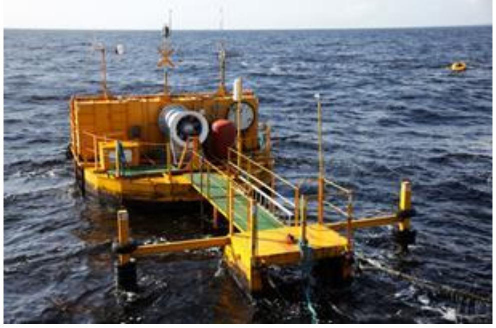
FEM	Finite Element Method
MDD	Motion-Dependent Device
MID	Motion-Independent Device
OTD	Overtopping Device
OWC	Oscillating Water Column
WEC	Wave Energy Converter

1.0 INTRODUCTION

Ocean waves are a huge, largely untapped energy resource, and the potential for extracting energy from waves is considerable. Wave Energy, as the name implies, is the energy of the waves, captured and converted into useful energy. Wave energy conversion is done with the aid of Wave Energy Converters (WEC). WEC devices can be categorized based on installation location and energy extraction method. WEC devices originally were installed at the shoreline. Due to higher energy density at open sea and more profitable, these have leaded to the installation of WEC at the near shore. The development of new energy extraction technique has initiated installation of WEC at offshore. For energy extraction technique, there are three different types of WEC devices (Figure 1), oscillating water column (eg; Ocean Wave Buoy), overtopping devices (eg; Wave Dragon) and wave activated bodies (eg; Pelamis).

a) Pelamis

b) Wave Dragon



c) Ocean Wave Buoy

Figure 1: Examples of WEC Devices

The major requirements for a WEC mooring system are to withstand the environmental loadings and to limit the excursion of the floating structure without affecting the power production efficiency [1, 2]. The purpose of mooring on WEC devices can be classified into two categories; Motion-Dependent Device (MDD) or Motion-Independent Device (MID).

A Motion Independent Device (MID) is defined as a device that required to move very little in one or more degrees of freedom to maximize the relative motion of the water in waves. Example of MID are floating Oscillating Water Column (OWC) and overtopping device (OTD). The MID mooring system is almost similar to conventional offshore floating structure, where the resonant period of the mooring is designed to be away from the resonant of the floating structure [2]. A Motion Dependent Device (MDD) is a device that required to be oscillated in waves to produce maximum relative motion between floating structure and the stationary Power Take-Off (PTO) system. The mooring system is designed to withstand high frequency, large amplitude motions, and high dynamic tensions in the mooring cables, especially when in resonance. This departs from the common desire to avoid resonant motions of floating structures, to a far more demanding regime than usual for mooring cables [3]. Example of MDD is heaving buoy and Wave Activated Body (WAB).

WECs will be installed in shallow to intermediate water depths, and in unsheltered areas with high wave energy densities. It can be expected these devices will experience a significant wave frequency and higher order wave frequency responses due to non-linearities within the waves [4, 5]. These locations also have significant tidal ranges and currents that can influence the behaviour of the device and its mooring system [4]. A reliable mooring system for WEC device is essential to provide high-energy extraction efficiency.

A review on design issues, requirements, and selections of mooring system for different types of WEC devices has been provided by Harris et al. [1]. While Johanning et al. [2] provide an overview on mooring design procedure for WEC. Davidson & Ringwood [6] also provide an overview on mathematical modelling of mooring system for WEC.

Offshore industry often requests for an accurate and efficient numerical model to predict the hydrodynamic behaviour of the floating structure with mooring system. The numerical model should be able to estimate the dynamic motion of floating structure accurately either the motion is dependent by the mass term, restoring force term or damping term. The amount of over-predict or under-predict in the prediction of motion of floating structure by the numerical model should be minimized to avoid large difference in the motion of the floating structure observed during the operating stage when compared to the numerical method result.

In offshore industry, the dynamic tensions of mooring lines are less significant or often assumed negligible when predicting the wave frequency of large floating structures [7, 8]. However, according to Johanning et al. [4], the mooring line responses are the dominant factor for station-keeping of WECs. The devices top-end motions are more likely to be at wave frequency. Hence, it cannot be neglected. To design a reliable mooring system for small marine renewable energy device, a full understanding on mooring line damping is required [4, 9]. Sources of mooring line damping partly from drag forces along the line and partly from the friction on the seabed. There are several methods to estimate the mooring line damping; model scale test, finite element method (FEM) and simple dynamic model.

Even though time domain can capture the nonlinearities of mooring line, it always overpredict the structure displacement when compared to model test [10]. This is due to no hull viscous damping is included during the structure damping estimation in WF response.

Siow et al. [11] and Siow [12] have proposed a new estimation method by modified diffraction theory and drag equation to analyze the wave frequency motion of offshore floating structures. These authors have developed a new estimation method (Koto-Siow's Method) to improve the damping of floating structure in WF response, but mooring line damping estimation is not included during estimation of the total damping force of a floating structure.

The objective of this paper is to review the mooring line damping methods and identify the best method to be applied in the estimation of mooring line damping for WEC device. Later, the mooring line damping will be added to the Koto-Siow's Method to analyse the hydrodynamic interaction of WEC platform and mooring system.

2.0 FUNCTION OF MOORING

The primary function of mooring system is to maintain the floating structure position under normal operating load and extreme storm load conditions. Due to small size of WECs and their being moored in relatively shallow waters, the effect of waves, tide and currents can be greater significance to the device than other conventional offshore platforms. According to Johanning et al. [4], the mooring line axial stretching and high-frequency top-end dynamic can modify damping and top-end loading of the WECs.

Even though there are many similarities between mooring system for offshore platform and WECs, there is also difference between these two mooring systems requirements. The major requirements for WEC mooring system, according to Johanning et al. [4] and VanZwieten et al. [9] are to withstand the environmental loadings and to limit the excursion of the floating structure without affecting the power production efficiency.

For MDD, a WEC is designed to have device resonant period match to mooring system at the wave frequency (WF) [2, 13]. This is supported by Johanning et al. [4] and Fonseca et al. [14], the WEC mooring system need to be designed with regards to dynamic in WF range. While for oil and gas offshore structure, the mooring system is designed to resonant far from exciting frequencies of the waves [15, 16].

Besides that, VanZwieten et al. [9], Falnes [17], and Fitzgerald & Bergdahl [18] mentioned that the WEC mooring system should be designed to keep the device at optimum orientation relative to the waves and could also be part of an optimum control system for the specific power bandwidth of WEC unit.

According to Johanning et al. [4], if WECs are installed in a “farm”, the device excursion should be restricted to prevent it from clash with other devices. Besides that, the mooring line footprint also should be constrained to ensure the mooring line for each device does not clash so it does not disturb the power extraction activity.

There several guidelines, rules and regulations for mooring system published by ship classification authorities such as API 1969, and DNVGL-OS-E301 [19]. However, this design, analysis and maintenance guidelines are more applicable for the oil and gas floating structures. This is due to high risk of substantial loss of life and the danger of environmental pollution in this industry. Different to offshore floating structure in oil and gas industry, WEC device usually operate unmanned, and no danger on major environmental pollution. In addition, unlike a typical offshore system, the design of moorings for a WEC device must consider reliability and survivability, and the need to ensure efficient energy conversion [4].

3.0 MOORING LINE DAMPING

The main source of total damping for moored structures is viscous hull, diffraction/radiation, wave viscous and mooring line damping [4, 20]. These damping playing a significant role in the reduction of low frequency motion of floating structures response. In this paper, the review is focusing on mooring line damping.

According to Huse [21], Huse & Matsumoto [22] and Huse [23], the mooring line damping in surge motion for moored vessels can provide as much as 80% of the total damping. Sources of mooring line damping partly from drag forces along the line and partly from the friction on the seabed. In addition, a mooring line may exhibit some internal damping which is considered negligible [24]. Vortex Induced Vibration (VIV) also is another source mooring line damping [20, 22]. According to Chakrabarti [25], the VIV in chain mooring line can be neglected while the VIV in wire line is too small. Brown & Mavrakos [20] and Brown et al. [26] commented that VIV can amplify the drag forces for wire lines but negligible for chain.

Mooring induced damping playing a significant role in both limiting the surge response and reducing the danger of moor failure [22, 24]. In slow drift cycle, when the moor is most taut, the horizontal spring of the moor can become large enough to cause surge resonance. Hence, surge damping is important in determining the maximum surge motion and maximum tension in the taut lines of the moored structure.

The pioneer work about mooring line damping was started by Huse [21], who applied the quasi-static method to investigate the mooring damping where the drag force was calculated using Morison’s equation. Since then, a series of works has been carried out to investigate mooring damping in surge motion.

3.1 Mooring Line Damping Estimation

To estimate the mooring line damping, researchers used model test, Finite Element Method (FEM) or simple analytical method. Model test is used to estimate the mooring line damping because it helps to provide crucial information about the complex linear and non-linear hydrodynamic behaviour of the floating structures total system, such as the total viscous damping contribution of the system, the coupled effects between floating structures and mooring lines, the transient green water and slamming forces, and other wave run-up effects that are difficult to evaluate through numerical simulation alone [27-31]. Thus, model tests are always used to validate design simulation by numerical tools.

Even though the model test method is more reliable compared to numerical tools, there still have limitations to estimate the mooring line damping of floating structures. The physical dimension of the wave basin often limits the possibility of modelling the complete floating structure and mooring system. In many cases the mooring system is replaced with mechanical springs chosen to match the static nonlinear characteristics of the mooring line. When this approach is followed, the dynamic behaviour of the mooring lines is clearly not modelled. [24]. In those cases where the tank is large enough to include the whole moor, the model scale is such that the mooring lines have a very small diameter. Matching the physical properties of the mooring line is tedious but possible; assuring that the hydrodynamic forces are correctly modelled is more difficult. [24]. Another issue is Reynold’s number discrepancy. The Reynolds numbers corresponding to the flow across the model mooring lines are exceptionally low and the cross-flow is probably quite different in nature from full scale. [24]. In order to limit the scale effect, ITTC [32] recommended scale ratios of less than 1:100 for reliable results in predicting the full-scale behaviour.

The mooring line damping can also be estimated using rigorous nonlinear FEM in time domain. There are many researchers used FEM to model the nonlinearities in mooring line dynamic [33-36]. Nakamura et al. [37] has presented a time domain FEM to calculate tensions of mooring chain. In this study, the added mass of the floating structures does not vary significantly with frequency. The author assumed that the slow drift motion occurs predominantly at the surge natural frequency.

Webster [24] has used a complex and time-consuming time domain FEM to examine the implication of mooring induced damping for two sensitive motions for ship-shaped platform, roll motions during operation and surge motion of single point mooring.

Brown & Mavrakos [20] have conducted comparative study on the dynamic analysis of suspended wire and chain mooring lines based on total 15 contributions using time and frequency domain method. From the study on mooring-induced damping, it is observed that, for the chain mooring line in shallow water, the quasi static method is under-predicted the line tension though they are in good agreement with time domain and frequency domain. While for the wire mooring line in deepwater, the results show wider variation.

Luo & Baudic [28] have conducted comparative study on turret moored FPSO response. The authors used FEM to model the mooring line dynamic and found that coupled time domain can captures the direct environmental loads and damping forces due to the mooring lines accurately similar to model tests.

Johanning et al. [4] used time domain FEM to study the mooring damping of WECs. The research shows that top-end dynamics have significant effect on the mooring line damping. When the top-end oscillating frequencies greater than 1 the dynamic effect will increase the mooring line damping.

Hall & Goupee [38] used a simple lumped-mass mooring line model to capture the dynamic mooring line characteristic of floating offshore wind turbine. From the data validation, it can be observed that the fairlead tensions are most sensitive to the transverse drag coefficient. From the coupled analysis, it is observed the fairlead tensions are under-predicted using this model. The authors suggested the under-predicted of heave motion leads to under-predicted of fairlead tensions. Besides that, this method has increased the simulation time by 10-15% compared to normal quasi-static mooring line model.

Xu et al. [39] have studied the effects of periods and amplitude of slow drift motions on mooring damping by using numerical oscillation simulations. They also used time domain FEM to solve mooring tensions induced by the surge harmonic oscillations at mooring line top end. Besides that, the influence of superimposed wave frequency motions responses is also been studied. From the study, it can be observed that the mooring damping is significantly affected by the oscillation amplitude and frequency. The oscillation with high amplitude and high frequency increased the mooring damping. Besides that, they also found that the superimposed wave frequency oscillation has significant effect on mooring line damping, the mooring damping will increase significantly when the wave frequency oscillation in considered.

The disadvantage of FEM is the numerical simulations are time consuming because the time step for the simulation must be small enough to resolve the wave frequency dynamic effects while on the same time the total duration must include enough low frequency cycles [40-43].

Quasi-static methods are considered by Huse [21], Liu & Bergdahl [44] and Bauduin & Naciri [43] to analyses the mooring line behaviour. For the quasi-static approach, the damping force is usually expressed in the form of drag force as predicted by the Morison equation. Huse & Matsumoto [22] have provided a simple procedure for calculating the energy dissipation in the mooring system for the case of low frequency sinusoidal surge motion of the vessel.

Bauduin & Naciri [43] have developed B-N model to calculate the low frequency mooring line damping induced by a fairlead surge motion. The author has proposed improvements on Huse’s model for mooring line induced damping by approximating the deformation of the line shape and the transverse velocity in more accurate ways respectively. The quasi-static approach used in this new model neglected the inertia effects in the mooring line, the seabed frictions and internal damping of mooring line. The drag forces acting perpendicular to the line are included while drag forces acting parallel to the line are neglected. The authors found that the new model shows significant improvement especially for shallow and intermediate water depth where the mooring line profiles in the near and in the far positions are drastically different. The B-N model has better prediction for transverse velocity at the fairlead compared to Huse’s model because Bauduin & Naciri [43] include the horizontal displacement ΔX to the normal displacement during energy dissipation calculation. It is observed that ratio of critical damping for B-N model is higher than the experimental due the presence of hull viscous damping during experiment is conducted. Hence, the mooring line damping estimation is under-predicted when compared to the finite element approach.

Fan et al. [41] have improved the quasi-static method in Huse’s model by include the seabed friction on catenary mooring system. The results of new improved quasi-static model are compared to the experimental results and Ansys AQWA. The authors observed the improved quasi-static model has less error for damping when compared to experimental results, while Ansys AQWA has bigger error. This is because Ansys AQWA does not include the seabed friction in the mooring line dynamic evaluation.

Hamilton & Kitney [45] used frequency domain method to determine the fairlead tension during preliminary design of mooring system. A quasi-static model has been used to model the mooring line behaviour. However, this method tends to under-predict the mooring line damping. Besides that, this method can only calculate for one degree of freedom for single mooring line.
Quasi-static method is not as rigorous as finite elements and not suitable for if non-linear cable responses are available [4, 46]. This method is also always underpredict the mooring line damping because it only use catenary equation to evaluate the mooring line pretension and displacement. Besides that, according to Johanning et al. [4] and Lin & Sayer [40] the prediction of the mooring line damping using quasi-static method requires an estimate of the drag coefficient of the mooring line and this could be a major source of error.

Simple analytical model also can be applied to estimate mooring line damping. Larsen & Sandvik [47] and Lie & Sødahl [48] have proposed a simplified frequency domain dynamic model of a single mooring line. They computed the dynamic mooring line tension and to estimate the extreme value of the tension during a short-term sea state.

Lie et al. [49] have developed an approach to predict mooring line damping coefficient by using simplified dynamic mooring line model (MIMOSA). The authors used viscous damper and a linear elastic spring coupled in parallel to represent the hydrodynamic damping and geometry stiffness. Both are related to the change of geometry of mooring line. Even though simplified dynamic model is more computationally efficient than time domain simulations, it always gives smaller damping coefficients. The relative error for mooring line tension between this method and time domain method is 5%.

4.0 INFLUENCE OF DRAG AND INERTIA COEFFICIENT TO MOORING LINE DAMPING

Brown & Mavrakos [20] and Xu et al. [39] have investigated the influence of drag and inertia coefficients to the mooring line damping. According to Brown & Mavrakos [20], by reducing the drag coefficient and increasing the inertia coefficient simultaneously, it is observed the mooring line total tension and damping are reduced. This is supported by Xu et al. [39], drag coefficient has significant influence to the mooring line damping. By increasing the drag coefficient, the mooring line damping also increases. However, inertial coefficient has little effect on the mooring line damping, though the inertial coefficient is increases.

5.0 WEAKNESS OF ANSYS AQWA

Fan et al. [41] and Fan et al. [50] have improved the quasi-static method for truncation mooring design. When compared to Ansys AQWA and model test, they observed that, Ansys AQWA does not include the seabed friction when estimating the mooring line damping using FEM.

Besides that, from a study conducted by Siow [12] and Siow et al. [51], they found that Ansys AQWA also does not include the viscous hull damping when calculating the total damping of floating structures. This has led to overestimate the structure motions.

6.0 CONCLUSIONS

Due to small size of WECs and their being moored in relatively shallow waters, the effect of waves, tide and currents can be greater significance to the device than other conventional offshore platforms. Besides that, the mooring line axial stretching and high-frequency top-end dynamic can modify damping and top-end loading of the WECs. In addition, mooring design and configurations has influence to structure motions and power absorption of the device. Hence, WEC and mooring system are basically a coupled system. The dynamic analysis of mooring system and structure motions should be done in time domain, so the mooring line nonlinearities can be captured accurately.

Method to estimate the mooring line damping on WEC has been reviewed. Most of the studies more focus on oil and gas floating structures compared to WEC. From the review, it is suggested that FEM is more suitable to analyse the mooring line dynamic because it gives better result than quasi-static method when compared to full-scale model even though the computational time to analyse FEM is higher than quasi-static method.

Besides that, the Koto-Siow's Method has improved the diffraction theory and drag equation, to include the hull viscous damping during estimation of unmoored vessel motion in WF response. As WEC and mooring system are basically a coupled system, the mooring line damping will be added-in the Koto-Siow's Method to evaluate the moored structure vessel in WF response.

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