NUMERICAL MODELING OF THE LIFESAVER MOORING SYSTEM FOR DEPLOYMENT AT WETS

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1. INTRODUCTION

The ocean energy group at HNEI provides key research support to the U.S. Navy's Wave Energy Test Site (WETS) at Kaneohe, Hawaii. As part of this support, the group undertakes numerical modeling to independently assess power performance of wave energy converters (WEC) deployed at the site. Beginning in 2017, the group has also begun in-house numerical modeling of mooring systems associated with these WECs in order to provide a third-party safety and performance check for developers and sponsors of WETS testing. The mooring system of a WEC device is a critical sub-system that can have a decisive effect on the performance and successive trials/deployment of the device in the open ocean. Lessons learned relating to mooring systems at WETS to date have underscored the importance of careful and early consideration of moorings in design and deployment planning. Mooring system modeling using commercial software such as ANSYS Aqwa or OrcaFlex is well established in the offshore industry, and recent analyses conducted by HNEI and DNV-GL have confirmed that careful modeling of the system can predict failure modes of the components before the system is deployed in the ocean [1]. Here we describe and model *preliminary designs* of the mooring system that is expected to be deployed with the Fred. Olsen BOLT Lifesaver device during upcoming trails at the WETS 30m berth. Component selection and modeling results obtained from ANSYS Aqwa will be discussed.

The Northwest Energy Innovations Azura device was deployed at the 30m WETS berth for about 18 months. The mooring system associated with this device performed well during these trials. For this reason, as well as obvious cost savings, it was determined that a key design emphasis was to reuse as much of the Azura mooring hardware as possible, with some components modified/adapted according to numerical modeling, for the Lifesaver device. The displaced masses of the devices are similar, but their motion characteristics are likely to differ significantly. The numerical modeling discussed here will shed light on these differences and thus guide the ultimate mooring design for Lifesaver. The Lifesaver WEC, with its direct-drive winch-based PTOs, actually relies on two mooring systems. The production moorings are highly pre-tensioned cables connecting the sea floor anchor, underneath the device, to winches on the device. These cables generate torque on the winches located on the deck of the Lifesaver WEC, as it responds to the waves, which results in power production [2]. These moorings are shown as red dashed lines in Figure 1. The storm moorings consist of slack cables that are expected to restrain the device and survive in the event of a failure in the production moorings, a scenario most likely in survival seas. The three cables shown in blue in Figure 1 form the storm mooring system. Each of these cables consist of a nylon riser connected to a buoy, which in turn is connected to a nylon hawser. In this paper we study *only* the storm mooring system in survival seas. The production moorings are not modeled in Aqwa and are shown as dashed lines in Figure 1 for illustrative purposes only. It is expected that results from modeling of the storm moorings will provide critical inputs for the mandatory permitting process.

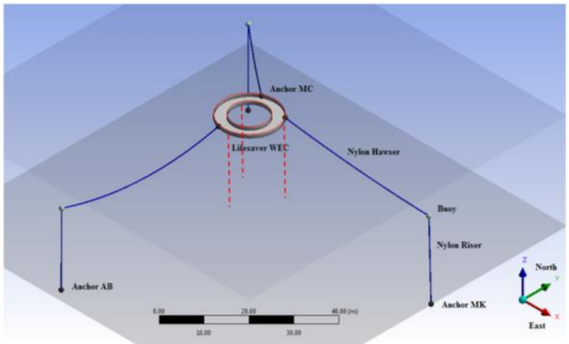

FIGURE 1. LIFESAVER DEVICE AT 30M BERTH AT WETS

The full adaptation of the Azura mooring system to fit the Lifesaver device may potentially include changes to all components of the system. However in this paper we focus on modifications to the hawsers only. During the previous deployment of Lifesaver at the 60m WETS berth, the developers felt that the pre-tension in the storm moorings may have affected the power performance of the device. For this reason, minimizing the pretension in the hawsers will be a key criterion in the modified mooring design. In the test cases considered in this paper, we begin by modeling Lifesaver with the existing mooring system that was used for Azura. The hawser is modified – both material and geometry - and comparisons are made on loading on the components. In Section 2, the components of the existing mooring system are discussed. Section 3 describes how Aqwa numerically models the components of the mooring system and solution methodology. A limited case study is presented and results are discussed in Section 4. The paper is concluded in section 5.

2. MOORING SYSTEM COMPONENTS

We first describe the main components of the existing mooring system that was used for the Azura device. The global X and Y axes point in the East and North direction respectively (See Figure 1). The water depth at the location is 30m. For convenience, we refer to Cable MC for the complete line starting at Anchor MC, ending at the device and consisting of the riser, buoy and hawser. Similarly for Cables MK & AB.

(a) Anchors: The Anchors MC, MK and AB are located at a radial distance of ≈ 48.6m from the device in the horizontal plane [3]. The design capacities of Anchors MC and MK are 25 tons and that of Anchor AB is 100 tons. Anchors MC & MK are similar in construction, consisting of wagon wheel frames rock-bolted to the seabed. In Figure 2, Anchors MC and AB are shown [3].

FIGURE 2. ANCHOR MC (LEFT), ANCHOR AB (RIGHT)

(b) Riser and Hawser: All risers and hawsers are 0.0635m (2.5 inch) diameter nylon ropes with a Minimum Breaking Limit (MBL) of 890kN (200,000lbs). The weight in air of this rope is 2.25kg/m (151lb/100ft). The Nylon rope and its elongation curve is shown in Figure 3 [4].

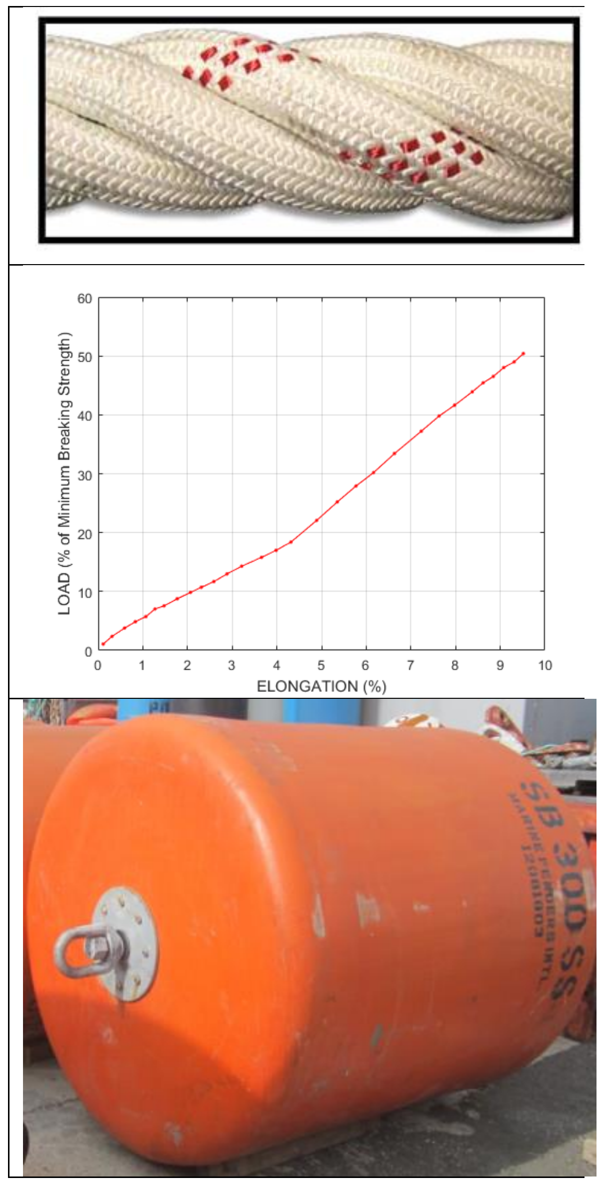

FIGURE 3. NYLON ROPE (TOP PANEL) AND ITS ELONGATION CURVE (MIDDLE PANEL). BOTTOM PANEL SHOWS THE SUB SURFACE BUOY OF 3000KG NET BUOYANCY.

Table 1 shows the lengths of risers and hawsers in each cable. To simplify modeling in Aqwa, small lengths of chain used in the Azura deployment at the ends of the ropes are replaced with additional nylon rope.

TABLE 1. LENGTHS OF RISER AND HAWSER

	Riser	Hawser
Cable MC	23m	39m
Cable MK	23m	39m
Cable AB	21.5m	40m

(c) Buoy: The buoys are sub surface SB-300 from Marine Fenders International, Inc. [5]. The structural mass of the buoy is 583kg, and it displaces 3583kg of salt water, giving it a net buoyancy of 3000kg in salt water. The overall height and diameter of the buoy are both 1.7m. The buoy is shown in Figure 3, bottom panel.

(d) Lifesaver: The Lifesaver WEC is a doughnut shaped device (Figure 1) with a displaced mass of 55t, outside diameter of 16m, inside diameter of 10m and floating at a draft of 0.438m[2].

3. AQWA MOORING MODEL

In this section we describe how the Aqwa solver numerically models components of the mooring system to obtain solutions in the time domain.

(a) Lifesaver: When connected to the mooring, the external loads on the device consists of (i) first order wave load (ii) second order wave drift load, (iii) current load, (iv)wind load, and (v) mooring cable load[6]. First order wave load, $F^{(1)}$, is the sum of Froude-Krylov and diffraction forces[1]. Second order drift loads, $F^{(2)}$, arise when we consider the instantaneous body position and instantaneous position of the free surface[7]. These drift loads consist of a steady component called steady drift, a component that depends on the difference of wave frequencies called slowly varying drift, and a component that depends on the sum of wave frequencies. The component that depends on the sum of frequencies has response periods much smaller than the wave loads and is generally important for structures such as Tension Leg Platforms. In this study this component is not included.

Current load, F_c is modeled as a drag force term in Morison's Equation [7] and equals,

$$F_c = \frac{1}{2}\rho C_d S|(u_f - u_s)|(u_f - u_s) \qquad (1)$$

In Eq. 1, ρ is the fluid density, C_d is the drag coefficient, and S is the device representative area. Symbols u_f and u_s are fluid particle velocity (vector sum of wave and current velocities) and structure velocities respectively. In the absence of current, the drag force resulting from the difference between the incident wave and structure velocity is accounted for with application of Eq. 1. In the Aqwa model, disc elements located on the device geometry generate the required viscous drag per Eq.1.

Wind load, F_w, is also modeled as a Morison drag force term and equals,

$$F_w = C_{dw}|u|u \qquad (2)$$

The wind drag coefficient, C_{dw}, has units of $N/(m/s)^2$ and is equivalent to the first four terms of Eq.1, including the constant, 1/2. The velocity u in Eq.2 is the relative velocity between wind speed and structure velocity.

(b) Mooring cable: The mooring cable, which consists of the rope and subsurface buoy, is modeled as a dynamic composite catenary line [6], which exerts a force F_m on the device.

(i)Rope: The forces on the rope consist of gravitational force, buoyancy force, structural inertia force, radiation force due to added mass, drag force due to current or cable motion, linear or nonlinear axial tension, and reaction at anchor and structure ends.

Since the axial stiffness of the nylon rope is comparatively *mildly* non-linear (See Figure 3) it has been modeled as,

$$EA = EA(\text{constant}) + a\varepsilon, \qquad (3)$$

where E is the Young's modulus of the cable with units of N/m^2, A is the cross sectional area of the cable with units of m^2, EA is the axial stiffness with units of N, a is a constant and ε is the strain of the cable. ε equals $\Delta L/L$, where ΔL is change in length and L is the original length. With Eq. 3 as the nonlinear axial stiffness, the tension in the cable is,

$$T(\varepsilon) = \int_0^{\varepsilon} EA d\varepsilon = EA(constant)\varepsilon + \frac{1}{2}a\varepsilon^2 \qquad (4)$$

Figure 4 shows how Eq. 3 compares with manufacturer's data.

For the nylon rope to experience added mass and (transverse) viscous drag forces, an added mass coefficient of 1 and drag coefficient of 1.6 has been used[8].

(ii)Buoy: The forces on the buoy are buoyancy/gravity force, structural inertia force, drag force due to current/buoy motion and radiation force due to added mass. The added mass of the buoy has been approximated as its displaced mass. A drag coefficient of 1 on a representative area of ≈2.9m^2 (1.7mx1.7m, See Section 2c) has been provided so that the buoy experiences drag force.

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[1] Froude-Krylov force is caused by the dynamic pressure of the incident wave on the structure. Diffraction force is due to the scattering of the incident wave by the structure

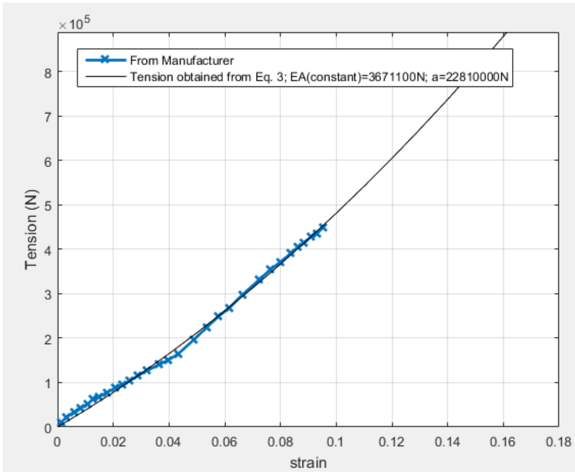

FIGURE 4. COMPARISON OF ACTUAL AND MODELED AXIAL STRAIN VS TENSION OF NYLON ROPE.

The equation of motion of the Lifesaver device in the time domain is [6],

$$\{\boldsymbol{M}+\boldsymbol{A}_{\infty}\}\ddot{\boldsymbol{X}}(t)=\boldsymbol{F}^{\mathbf{1}}(t)+\boldsymbol{F}^{\mathbf{2}}(t)+\boldsymbol{F}_{\boldsymbol{c}}(t)+\boldsymbol{F}_{\boldsymbol{w}}(t)+\boldsymbol{F}_{\boldsymbol{m}}(t)-\boldsymbol{K}\boldsymbol{X}(t)-\int_0^t \boldsymbol{h}(t-\tau)\ddot{\boldsymbol{X}}(\tau)d\tau \qquad (5)$$

In Eq. 5, t represents time, $\boldsymbol{M}$ is structural mass matrix, $\boldsymbol{A}_{\infty}$ is the added mass matrix at infinite frequency, $\boldsymbol{X}$ and its (time) derivative represent displacement and acceleration. $\boldsymbol{K}$ is the hydrostatic stiffness matrix. The $\boldsymbol{A}_{\infty}$ term and the last term in Eq. 5 arise from using the convolution integral for calculating the radiation forces[9][6]. The rest of the terms were described previously. $\boldsymbol{F}^{\mathbf{1}}$, $\boldsymbol{F}^{\mathbf{2}}$, radiation forces, and $\boldsymbol{K}$ are calculated in Aqwa using a Boundary Element Method. $\boldsymbol{F}^{\mathbf{1}}$ and $\boldsymbol{K}$ can also be estimated based on instantaneous wetted surface, although this option was not used in this study.

4. CASE STUDIES

Table 2 presents the case studies that have been carried out. We begin by modeling the Lifesaver in the existing mooring system, which is Case 1. Case 2 uses a longer nylon rope of length 42m. This length gives sufficient slack to reduce pretension in the hawser. Cases 3 & 4 make use of studless chains (also 42m in length) of different diameters.

TABLE 2. HAWSER SPECIFICATIONS FOR CASE STUDY

	CableMC	CableMK	CableAB
Case1	Nylon (L=39m D=0.0635m)	Nylon (L=39m D=0.0635m)	Nylon (L=40m D=0.0635m)
Case2	Nylon (L=42m D=0.0635m)	Nylon (L=42m D=0.0635m)	Nylon (L=42m D=0.0635m)
Case3	Chain (L=42m D=0.0125m)	Chain (L=42m D=0.0125m)	Chain (L=42m D=0.0125m)
Case4	Chain (L=42m D=0.025m)	Chain (L=42m D=0.025m)	Chain (L=42m D=0.025m)
(i)Nylon *MBL*= 890kN; *Weight/Meter (water)*=0.25kg/m (ii) Chain: 0.0125m diameter *MBL*=132kN [10] *Weight/Meter(water)*=2.7kg/m [10] (iii)Chain: 0.025m diameter *MBL*=514kN[10] *Weight/Meter in water*=10.8kg/m[10] Added Mass Coefficient for Chain=1 [8] Transverse Drag Coefficient for Chain=2.4 [8] Longitudinal Drag Coefficient for Chain=1.15 [8]			

TABLE 3. HAWSER PRETENSION WITHOUT ENVIRONMENTAL FORCING

	CableMC	CableMK	CableAB
Case1	3.4kN	3.3kN	2.5kN
Case2	<0.5kN	<0.5kN	<0.5kN
Case3	1.7kN	1.7kN	1.4kN
Case4	4.7kN	4.5kN	4.0kN

It is pointed out that in all the cases the existing nylon riser is used. We first estimate the pretension on the device without any environmental forcing. These results are given in Table 3. A slack nylon rope generates minimum pretension – Case 2. Switching to Chain (Cases 3 and 4) increases the pretension as the weight/meter is larger for chain (for same length). Note that without environmental loads, the anchor uplift and tension in the riser approximately equals the net buoyancy of the buoy ≈ 29kN.

Environmental Forcing: Environmental forces are irregular seas, current, and wind. Only survival seas are considered in this study. Li and Stopa [11] carried out extensive study of sea states around Hawaiian Island sites and estimated the 100-year significant wave height and peak period at the 30m site to be 6.2m and 14.4s respectively. The most common direction is ENE. Wind and current of 56knots and 2knots [1] respectively are also included. They are collinear with the wave direction. In Aqwa, a PM spectrum is applied to generate the irregular sea.

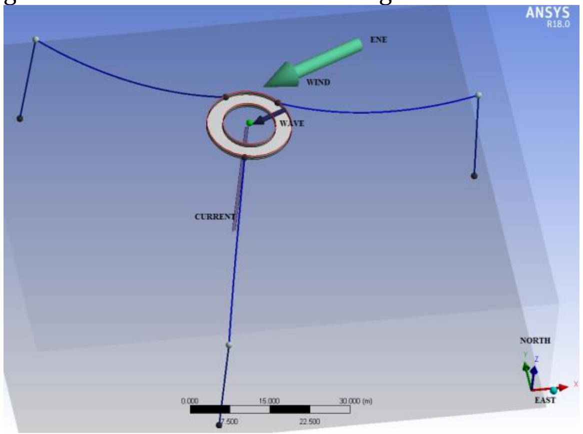

FIGURE 5. ENVIRONMENTAL LOADS ON MOORING SYSTEM. ANCHOR MK IS ON THE RIGHT OF THE FIGURE. THE DIRECTION OF FORCING IS ENE

Figure 5 shows the device connected to the mooring and all environmental loads. With this direction we expect the maximum loading to be on the Cable MK and Anchor MK. The ratio of MBL to maximum tension in the hawser and riser is given in Table 4.

TABLE 4. RESULTS FOR CABLE MK

	MBL/(Max.Riser Tension)	MBL/(Max.Hawser Tension)
Case1	4.4	5.2
Case2	5.0	5.7
Case3	4.7	<1
Case4	3.8	2.5

The ratios given in Table 4 may be loosely interpreted as safety factors. The 12.5mm chain in case 3 is clearly inadequate. The slack nylon rope in Case 2 shows promise. In this case the factor of safety (FS) for riser and hawser are large. FS on the anchor uplift (ratio of anchor capacity to maximum anchor uplift) is comparable to that of the Azura device and so deemed safe. It is pointed out that, in the case of Azura, when the wave loads and hydrostatic forces were calculated based on instantaneous wetted surface, a noticeable reduction on the anchor and cable loading was observed. We plan to include this option in the Lifesaver case as well, which may further reduce the loading. It is also observed that with larger diameter chain, the load on the anchor is also higher, apparently due to the larger inertial forces generated by the heavier chain.

5. CONCLUSIONS

The limited case studies presented in this paper examine whether the existing mooring system, used previously for Azura, is sufficient for the Lifesaver device. Important components of the mooring system are presented and a concise description of how these components are numerically modeled in ANSYS Aqwa is given. The study indicates that a longer nylon hawser generates minimum loading on all important components of the mooring system. Also a sufficiently strong chain (instead of the nylon rope) for the hawser can add enough pretension on the device so as to negatively impact its power performance. In the future, wave loading and nonlinear hydrostatic forces based on instantaneous wetted surface area will be included in the modeling.

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