A brief review on the hybrid taut mooring with intermediate buoy for the wave energy converter

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Introduction

As the renewable energy market grows, there are efforts to harvest the energy in the ocean, such as the offshore wind turbine and wave energy converter. Efficiency of each of renewable energy devices are still low with intermittency issue, therefore, a large size of renewable energy farm is considered to reduce the installation and operational costs. The mooring system for the wave energy converter which absorbs the wave energy by vertical motion should be designed not to affect the vertical motion characteristics, and to have a small footprint (small anchoring radius) for farm and potential conflict with fishery industries. Then, the hybrid taut mooring with intermediate buoy system is inspired by (1; 2), and experimental comparison on this mooring system and conventional mooring system is also conducted (3). However, a theoretical review nor design aspects on this mooring system are not well described. In the present study, a simplified theoretical model is introduced based on the quasi-steady state and validated against the numerical model and experimental campaign.

A Simplified Model

A simplified taut mooring with intermediate buoy model is introduced based on the quasi-steady state, and a schematic view is depicted in Fig. 1.

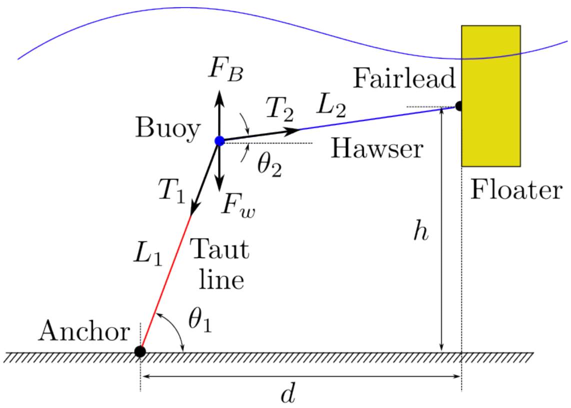


Figure 1. Simplified vertical buoy mooring

Horizontal and vertical distance between anchor and fairlead and lengths of hawser and taut lines, effective underwater weight of buoy are set to known, the position of buoy and acting tensions both for hawser and taut lines are unknown. The kinematic conditions of taut and hawser lines can be given in:

$$L_1 \cos\theta_1 + L_2 \cos\theta_2 = d \tag{1}$$
$$L_1 \sin\theta_1 + L_2 \sin\theta_2 = h \tag{2}$$

Introducing $x = L_1 \cos\theta_1$ and $y = L_2 \cos\theta_2$, the analytical expression for two angles can be given in:

$$x = \frac{Kd \pm h\sqrt{L_1^2(h^2+d^2) - K^2}}{(h^2+d^2)}, \qquad y = h - x \tag{3}$$

with $K = \left(d^2 + h^2 + L_1^2 - L_2^2\right)/2$. It implies that the position of buoy can be determined by distance between anchor and fairlead points, and lengths of two connected lines. It is also important to show that the roots given in (3) are real-valued solution. Therefore, the below relation should be satisfied:

$$L_1^2(h^2+d^2) - K^2 \geq 0 \quad \leftrightarrow \quad \left[(L_1+L_2)^2 - R^2\right]\left[(L_1-L_2)^2 - R^2\right] \leq 0 \tag{4}$$

with $R^2 = h^2 + d^2$. Then, the below condition should be satisfied to have real-valued solution:

$$|L_1 - L_2| \leq \sqrt{h^2 + d^2} \leq L_1 + L_2 \tag{5}$$

It is interpreted that the summation of two mooring lines $L_1 + L_2$ should be equal to or greater than the minimum distance from the anchor to the fairlead point, as shown in Fig. 1. And it should be also remarked that double roots exist in (3), it can be easily identified from the relation $y = h - x$ that:

$$x^{(1)} \leq x^{(2)} \quad \text{and} \quad y^{(1)} \geq y^{(2)} \quad \leftrightarrow \quad \theta_1^{(1)} \geq \theta_1^{(2)} \quad \text{and} \quad \theta_2^{(1)} \leq \theta_2^{(2)} \tag{6}$$

Then, the two candidates of buoy position which connect the anchor and fairlead points can be shown in Fig. 2 and we can already interpret that the position of buoy cannot be determined by the kinematic conditions, but the dynamic condition (force equillibrium) is required.

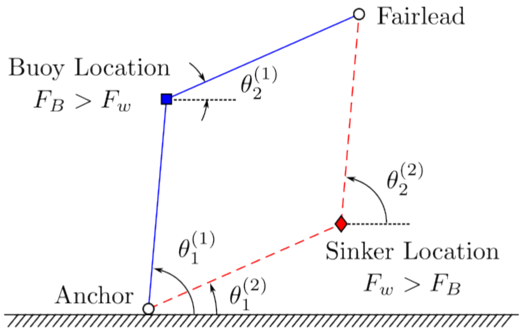


Figure 2. Two roots of simplified buoy model

The force equilibrium can be given in:

$$T_1 \cos\theta_1 = T_2 \cos\theta_2 \tag{7}$$
$$T_1 \sin\theta_1 = T_2 \sin\theta_2 + F_0 \tag{8}$$

with $F_0 = F_B - F_w$ is the effective underwater weight of buoy, F_B and F_w are buoyancy and weight of buoy. Then, the acting tensions on the taut and hawser lines are given in:

$$T_1 = \frac{F_0 \cos\theta_2}{\sin(\theta_1 - \theta_2)}, \qquad \text{and} \qquad T_2 = \frac{F_0 \cos\theta_1}{\sin(\theta_1 - \theta_2)} \tag{9}$$

It can be also identified that the provided tension to the floater T_2 is function of inclined angle of two lines θ_1 and θ_2 and effective weight F_v. And the force equilibirum gives a relation that:

$$x = L_1 \cos\theta_1 = \frac{\frac{T_2}{L_2} d + F_0}{T_1/L_1 + T_2/L_2} \tag{10}$$

The taut line angle θ_1 depends on the sign of F_0, and we can easily identify two cases that the taut line angle θ_1 of the first case of $F_0 > 0$ (Buoy) is smaller than the second case of $F_0 < 0$ (Sinker). The horizotanl and vertical stiffness (k_h and k_v) can be obtained by taking derivative of horizontal and vertical forces $F_h = T_2 \cos\theta_2$ and $F_v = T_2 \sin\theta_2$:

$$k_h = \frac{\partial F_h}{\partial d} = \frac{\partial F_h}{\partial \theta_1}\frac{\partial \theta_1}{\partial d} + \frac{\partial F_h}{\partial \theta_2}\frac{\partial \theta_2}{\partial d} = \frac{F_0}{\sin^3(\theta_1 - \theta_2)}\left(\frac{\cos^3\theta_2}{L_1} + \frac{\cos^3\theta_1}{L_2}\right) \tag{11}$$

$$k_v = \frac{\partial F_v}{\partial h} = \frac{\partial F_v}{\partial \theta_1}\frac{\partial \theta_1}{\partial h} + \frac{\partial F_v}{\partial \theta_2}\frac{\partial \theta_2}{\partial h} = \frac{F_0}{\sin^3(\theta_1 - \theta_2)}\left(\frac{\sin^2\theta_2\cos\theta_2}{L_1} + \frac{\sin^2\theta_1\cos\theta_1}{L_2}\right) \tag{12}$$

It can be easily identified that the $\theta_1 \in [0, \pi/2]$ to maintain the hawser line tension, and the sum of two lines cannot exceed the diagonal distance between anchor and fairlead since the elasticity is not considered. These two facts provide us hybrid taut mooring system regions as shown in Fig. 3. The considered hybrid taut mooring only acts when the hawser line is under the tension only $x_{buoy} \geq x_{anchor}$ and kinematic condition

$L_1 + L_2 \geq \sqrt{d^2 + h^2}$ is satisfied. If the fairlead offset moves toward the anchor point too much, the hawser line will behave as the catenary mooring, therefore the hawser's catenary due to its underwater weight will provide the mooring loads. In contrast, the fairlead moves far away from the anchor ($L_1 + L_2 < \sqrt{d^2 + h^2}$), the mooring loads are mainly provided by the elasticity of two lines in parallel.

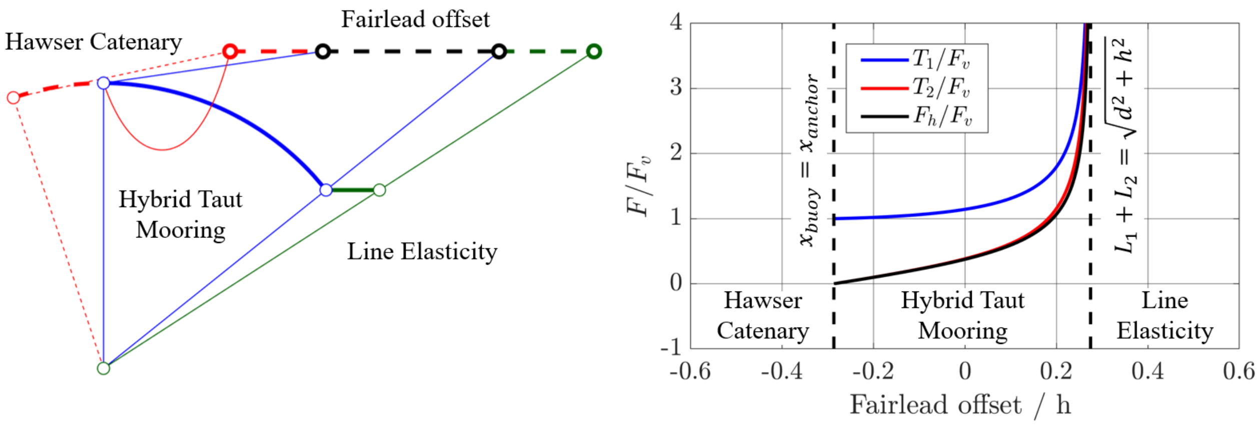


Figure 3. Hybrid Taut Mooring System with respect to the fairlead offset

To validate the hybrid taut mooring model, the numerical solver OrcaFlex is used. The horizontal and vertical distances between anchor and fairlead point is set to 50 m and 60 m, with $m = 1$ ton, $V = 2\ m^3$, with $\rho = 1\ ton/m^3$ are set. The axial stiffness of lines are set to $EA = 10^6 kN$ in the OrcaFlex to be rigid enough. By changing the lengths of line, the obtained buoy position, and tension are compared in Table 1. The position of buoy and tensions shows a good agreements with each other.

Table 1. Comparison of analytic and numerical results for buoy location and line tension

Case	L_1 [m]	L_2 [m]	Buoy Location				Tension			
			Analytic		Numeric		Analytic		Numeric	
			X [m]	Y [m]	X [m]	Y [m]	T_1 [kN]	T_2 [kN]	T_1 [kN]	T_2 [kN]
1	40	40	18.347	35.544	18.345	35.546	18.357	10.640	18.353	10.636
2	45	40	13.885	42.804	13.884	42.805	12.193	4.167	12.193	4.167
3	50	40	11.652	48.623	11.652	48.624	10.856	2.639	10.856	2.639
4	50	45	6.215	49.612	6.215	49.613	10.186	1.301	10.186	1.301
5	50	50	1.012	49.990	1.012	49.990	9.849	0.204	9.849	0.204

Some results & Discussion

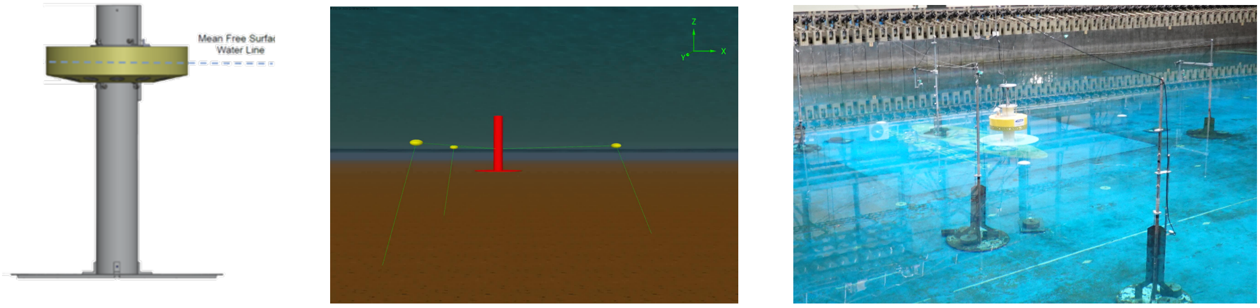
A single point wave energy converter (WEC), that consists of a spar with a heave plate and the heaving floater, is considered as shown in Fig. 4a. The wave energy is taken from the relative vertical motion of spar and floater. Three hybrid taut mooring system is employed for the position keeping of WEC (Fig. 4b) and the experimental setup is also shown in Fig. 4c. In the design of hybrid mooring system, it is important to consider the allowable offset and natural periods of WEC system. We can identify that the position of buoy, and active zone of hybrid taut mooring is determined by the horizontal/vertical distances and taut/hawser line lengths. Then, the pretension and horizontal and vertical mooring stiffness can be adjusted by the effective underwater buoy weight. Therefore, we can establish the following design steps for hybrid taut mooring system:

(1) The taut line length is determined from the horizontal and vertical distance. It should be always submerged in the water to prevent the snapping due to change of buoyancy. Therefore, the submergence depth can be determined by considering the tide height, storm surge and wave condition.

(2) The hawser line length can be determined from the positive and negative allowable offset of floater. Both positive and negative offset should have the same magnitude for any direction of environment condition.

(3) The effective buoy weight can be determined to control pretension of lines and mooring stiffness.

From the parametric study on the tensions and stiffness of hybrid taut mooring system based on the above principles, the mooring configuration given in Table 2 is determined for the validation.



(a) Floater **(b)** Mooring configuration **(c)** Experimental setup

Figure 4. Wave energy converter with three hybrid taut mooring system

From the parametric study, the natural periods of WEC's motion with three hybrid taut mooring can be obtained, and compared in Table 3. It shows that the proposed a simplified mathematical model is useful in the early design stage of hybrid taut mooring system. It is also preferred to avoid the natural periods of horizontal motions in the region of wave period. In the parametric study, these two disadvantages are identified: (1) A relatively large effective underwater buoy weight is required to reduce the surge/sway's natural periods, to resist the steady environmental loads such as wave drift force, current and wind loads. It can result in a large tension on the anchor, a special device such as suction pile would be installed. (2) A relatively large tension of hawser line makes the natural period of yaw be short. In (4), the yaw motion stiffness due to pretension is discussed and it shows that the large pretension affects the floater's yaw natural period. The present model does not consider the elasticity of taut and hawser lines which is not realistic, since the synthetic ropes are adopted due to its light weight with high stiffness. The elasticity can be easily implemented in the proposed model by updating the adjusted line lengths with iterative procedure.

Table 2. Experimental setup (Real Scale)

Item	Notation	Value
Scale ratio	-	23.62
Water depth	-	72.40 m
Buoy underwater weight	F_0	723.64 kN
Hor. & Ver. distance	d & h	94.48 m & 51.66 m
Taut & Hawser length	L_1 & L_2	56.78 m & 72.28 m
Taut & Hawser tension	T_1 & T_2	789.2 kN & 308.6 kN
Allowable floater offset	-	[-22.2m, 21.4m]

Table 3. Natural periods (Real scale)

Motion	Eigen.	Numerics	Exp.
Surge	48.5 s	53.0 s	54.2 s
Sway	48.5 s	53.0 s	54.8 s
Heave	37.0 s	37.4 s	37.3 s
Yaw	18.6 s	19.1 s	18.2 s

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