International Journal of Marine Engineering Innovation and Research, Vol. 9(3), Sept. 2024. 495-503
(pISSN: 2541-5972, eISSN: 2548-1479)

Integrity and Safety Factors of Asymmetric Mooring Line Arrangement on Ocean Farm ITS

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(Received: 15 July 2024 / Revised: 5 August 2024 /Accepted: 24 August 2024)

***Abstract*— An offshore aquaculture model called OFITS has been designed to be installed in the Indonesia Ocean. The OFITS structure consists of an underwater fish cage and living quarters at the superstructure. An asymmetric mooring line arrangement is proposed to be applied at OFITS. This paper aims to analyze the integrity and safety factor of the asymmetric mooring line arrangement used on OFITS in the presence of environmental load. The proposed asymmetric mooring line arrangement has 14 lines with a specified configuration. There are 10 mooring lines installed on the front side in line with the incoming waves and 4 others installed behind the cage. A nylon line with a diameter of 42 mm and a length of 70 m is used as the mooring line attached to a steel anchor weighing 0.25 tons. The analysis method for the moored cage motion uses the time domain analysis. The mooring line's integrity analysis results show that the maximum tension result is 18.55 tons, with a safety factor of 2.07. It can be concluded that the proposed asymmetric arrangement mooring has good integrity and meets the safety factor requirements of the DNVGL standard, with a minimum safety factor of 1.45.**

Keywords— Integrity, Safety Factor, Asymmetric Mooring Line, Offshore Aquaculture.

I. INTRODUCTION

In the current global market, there is a growing demand for the supply of fishing commodities. However, it promotes the growth of overfishing activities since it is not counterbalanced by effective fisheries management. In 2017, the world's marine fish stocks were classified as overfished by 34.2%. This constant trend is warranted by more comprehensive efforts to combat overfishing [1]. Consequently, efforts in marine aquaculture are required to repair and enhance the state of marine fisheries damaged by overfishing. Across regions, aquaculture development has been exhibiting various fluctuations in growth. In Asia, the largest producer region of aquaculture, growth in the period 1990-2020 was relatively steady at around 3%, although with decreasing growth rates [2]

Fish, which can support food security and nutrition, are a valuable resource that may be compromised by overfishing in Indonesia. Furthermore, the ocean is impacted by climate change, which lowers fish harvests. Thus, marine aquaculture initiatives in Indonesia are necessary to support and enhance the state of marine fisheries. [3].

The fish production model in this aquaculture system relies on its natural environment, enclosed in specially built structures in open sea areas. Offshore aquaculture technology is being developed as a viable alternative to marine-based aquaculture. One of the goals of offshore aquaculture development in open ocean settings is to build a sustainable technology model and to remove or lessen the influence on coastal ecosystems.

Offshore aquaculture offers numerous benefits, such as improved water quality, optimal locations, steady fish production, and increased economic prospects. However, it also confronts substantial environmental challenges, including the forces of currents, winds, and waves. The infrastructure for offshore aquaculture needs to be comprehensive, accommodating various necessities like feeding systems, surveillance systems, nets for predator protection, and a system for segregating deceased fish [4] [5]. Several developed countries, including the United States, Japan, Norway, and Russia, have advanced in offshore aquaculture technology.

Furthermore, the aquaculture cage's site must be reasonably remote from shipping routes and maritime constructions such as undersea pipelines and cables. Many coastal locations in the Java Sea in Indonesia have been developed as shipping lanes, fishing ports, and public and private commercial ports, and hence, aquaculture cages cannot be erected there or in a more restricted position [6]. Furthermore, Indonesia still has a large potential for aquaculture in the open sea. Therefore, developing offshore aquaculture in the open ocean is essential, and it may be a solution for future fish farming endeavors.

Fish farming in the open sea, particularly in Indonesia, might minimize social tensions caused by rivalry for croplands. According to 2017 data, Indonesia has a potential area of maritime cultivation of 12.12 million hectares, with a usage rate of only 325,825 hectares, or 2.7% [7]. Establishing a model of offshore aquaculture

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technology compatible with the open sea environment is required to boost marine fishing production and food security in Indonesia.

The OFITS model is a semisubmersible net cage concept with a spread mooring system. This concept has the advantage of lessening environmental load reactions [8]. The OFITS will be applied to cultivate yellow-fin tuna in the Indonesian Ocean. The model is a new approach for traditional fisheries producing tuna fish in Indonesia.

OFITS is floating rigid aquaculture cages, which adopt a design concept distinct from floating aquaculture flexible cages. The structure comprises steel pipe frameworks for enhanced strength, stiffness, and stability, with HDPE pipes serving as floaters. The structure is designed to endure significant wave action and integrates various management-related amenities, including feed storage, living quarters, and a harvest deck.

Most offshore aquaculture structures in the world are secured to the seabed by a symmetrical arrangement of mooring lines using a catenary mooring type. The mooring keeps the floating structure stationary in its designated location [9]. Li et al. optimized the design of the mooring system for an offshore aquaculture platform. The model is an offshore aquaculture structure shaped like a rectangle, measuring 64.05 m in length and 17.05 m in width. The design of a symmetric catenary mooring system starts with a multi-objective optimization problem, which is solved by considering dynamic constraints and survivability [10]. Shen et al. developed a dependable instrument to assess the survival parameters of the system. The system's modeling is succinct, encompassing both structure and hydrodynamics. A floating collar with buoy support houses the fish farm, consisting of two concentric tubes secured symmetrically with a bridle, frame, and mooring system and two tubes. Dominant physical parameters for modeling the system were determined through numerical sensitivity analysis [11]. Xu et al. devised a hydrodynamic model for a fish cage and a symmetrical mooring grid system, employing the lumped mass method and rigid body kinematics. The propagation of waves in multiple directions in the open sea influences the hydrodynamic performance of fish cages and symmetrical mooring grid systems [12]. Li and Jiang proposed an optimized integrated design for symmetrical mooring systems. The methodology combines experimental design, screening analysis, time-domain simulations, and meta-based optimization in its approach. The vessel-shaped offshore fish farm's symmetrical mooring system was designed according to the ultimate limit state [13]. Yu et al. studied experimental and numerical modeling on a symmetric spread mooring system adopted with a 4 × 2 mooring system under different environmental variables (wave and current), including bottom-sitting survival and floating operational settings [14]. Liu et al. examined the semi-submersible aquaculture platform's dynamic behavior by combining the Morison equation and potential flow theory. The aquaculture system consisted of a symmetric mooring system, a main frame, and fish nets. This study examines the influence of regular waves on the semi-submersible aquaculture platform's dynamic response under nonlinear catenary and linear elastic mooring within a symmetric mooring system [15].

An asymmetric mooring line arrangement is proposed for OFITS. The idea behind this arrangement is to install an uneven number of mooring lines. The loads' possible size and the environmental loads' direction determine how they are configured. This paper aims to examine the integrity and safety factor of the asymmetric mooring line arrangement on OFITS when there is an environmental load.

II. METHOD

A. Numerical Model

OFITS's unique aquaculture structure and asymmetric mooring line arrangement model pose a new technical challenge for researchers in creating a numerical model encompassing the aquaculture structure and netting that complies with the classification standard's safety factor and adequate integrity.

In normal and extreme conditions, the asymmetric mooring design must keep the aquaculture structure stationary within the specified range. This repetitive process requires a comprehensive and integrated approach. It involves the specifics of the aquaculture structure, environmental conditions, hydrodynamic analysis, gravitational, buoyancy, and mooring tension analysis.

B. Asymmetric Mooring Line Arrangement

The concept of an asymmetric mooring line arrangement in OFITS involves installing a varying number of mooring lines. These configurations depend on the potential intensity of the loads and the direction from which environmental loads are expected.

This study proposes an asymmetric mooring line arrangement consisting of fourteen lines with a specific configuration. Ten mooring lines are positioned at the front of the cage, aligned with the direction of the incoming waves, and four are positioned at the rear of the cage. In detail, facing the wave approach, the front of the OFITS has five mooring lines on each of the right and left sides. At the rear, near the beach, there are two mooring lines on both the right and left sides shown on Figure 1.

The mooring system comprises two parts: an underwater mooring line and a mooring line grid. The mooring lines are made of nylon rope, and their dimensions and material properties are detailed in Table 1. The floating buoy has a maximum capacity of 1 Ton. Each steel anchor used for mooring weighs 0.25 tons. The mooring lines should have a safety factor of 1.67 [16].

TABLE 1.
MOORING LINE PROPERTIES

Mooring Line	Weight (kN)	Minimum Breaking Load (kN)	Length (m)
Nylon 26 mm (Underwater Mooring Line)	0.4	112	70
Nylon 18 mm (Mooring Line Grid)	0.2	66	15

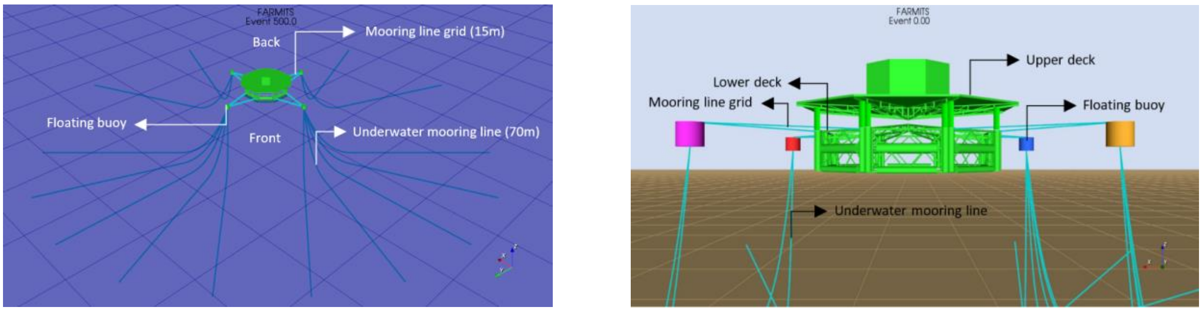


Figure 1. OFITS Mooring Configuration

C. OFITS Structural Data

The OFITS structural design features a tetrahedron-shaped, semi-submersible framework that is highly stable and exhibits minimal motion response. The OFITS structure is segmented into three main sections: the upper deck serves as living quarters for tourists, the lower deck provides space for officers conducting fish farming operations, and the submerged section houses the fish farming nets. The primary dimensions of the OFITS design are detailed in Table 2 and Table 3.

OFITS collected several structural weight data, all of which are necessary to analyze the mooring system under ultimate limit state conditions (ULS), as shown in Table 3.

D. Research Location

Figure 2 illustrates Sidoasri Beach, in Malang Regency, East Java Province, where OFITS were installed in the Indonesian Ocean. This research significantly contributes to food security in the fisheries sector and adheres to sustainable development goals (SDGs) principles, focusing on responsible consumption and production. The Team sought support from the fishing and village communities, Tourism Awareness Group (POK-DARWIS), Sido Lestari Community Monitoring Group (POKMASWAS), and Pondokdadap Port and Implementation of Maritime and Fishery Resources (P2SKP) through surveys and hearings before building the OFITS prototype.

TABLE 2.
SPECIFICATION OF OFITS

Items	Size	Units
Upper deck section		
Diameter of the upper deck	19.82	m
High of the upper deck	2.50	m
Diameter of the living quarter	8.00	m
Lower deck section		
Diameter of the lower deck	16.00	m
Width for a sidewalk	2.00	m
Underwater section		
Diameter of nets	16.00	m
Depth of nets	7.00	m
Draft and Displacement		
Draft	1.60	m
Displacement	32.89	ton

TABLE 3.
GENERAL STRUCTURAL WEIGHT DATA OF OFITS

Description		Weight	
		Ton	Kg
Dead Load	Top Deck	6,12	6.120
	Lower Deck	4,46	4.460
	Connector	0,35	350
	Boat Landing	0,5	500
	Buoyancy Frame	3,94	3.940
Hotel	Hotel Furniture	2,58	2.580
	Hotel Roof	0,42	420
Railing		1,54	1.540
Net + Sinker		0,83	830
Live Load (10 orang)		1,00	1.000
Floater		5,35	5.350
Plate Joint (Stiffeners)		5,00	5.000
Total		32,08	32.080

E. Environment Data

Environmental data from Sidoasri Beach in the Indonesian Ocean, including wave height, wave period, wind speed, and currents, were acquired through field observations and satellite extraction. At 06:00:00.000 and 00:00:00.000, observations were taken at longitude 112°46'47.82"E and latitude 8°23'27.27"S. The environmental data are tabulated in Table 4.

F. Net Data

Selecting the right materials and features for the net is crucial for designing an offshore aquaculture system. The net in the aquaculture cage must be strong enough to withstand the wave forces affecting the cage frame. A cage system adjusts dynamically to external factors, such as waves. Table 5 presents the net data.

G. Modeling of Structures

In modeling OFITS, it is assumed that steel frame structures and HDPE Floater are represented as tubular members. All the mentioned components, including railing systems, floor decks, sinkers, springs, plate joints, hotel structures (furniture, walls, and roofs), and humans, are modeled as loads. The life-raft decks and connecting plates of each member were omitted from the model. The OFITS draft proposes an average depth of 1.6 m and a stationary seabed anchor. The crew identified a group of 10 people with a total mass of 100 kg. OFITS specifications are presented in Table 6.

H. Response Amplitude Operator

Calculating the maximum tension in the OFITS mooring line involves several steps: modeling the OFITS structure, modeling the mooring system, analysis of motion response, and, ultimately, analysis of maximum tension. The frequency domain's Response Amplitude Operator (RAO) is utilized for the motion response analysis. The equations for surge, heave, and pitch motion in the frequency domain are presented [17] [18]:

$$\sum_{i=1}^{3}[-\omega^2\{M_i + A_i(\omega)\} + i\omega C_i(\omega) + K_i]X_i(\omega)e^{i\omega t} = F_i(\omega) \quad (1)$$

where M_i is mass, ω is the angular frequency, $A_i(\omega)$ is hydrodynamic added mass, $C_i(\omega)$ frequency-dependent damping, K_i hydrostatic stiffness, $X_i(\omega)$ dynamic response vendor, and $F_i(\omega)$ dynamic load in the frequency domain for degrees of freedom.

In a linear system, the RAO chart plots the response amplitude against the wave frequency or period:

Figure 2. Location of OFITS Installation

TABLE 4.
ENVIRONMENTAL DATA IN SIDOASRI BEACH IN THE INDONESIAN OCEAN

Parameter		Unit	100 – years
Topography	Sea depth	m	20
Wave	Height (Hs)	m	3,1
	Period (Tp)	S	7,63
Wind	Speed (Vw)	m/s	8,61
Current	Speed (Vc)	m/s	1,72

TABLE 5.
NET SPECIFICATIONS

Net Specifications	
Mesh Dimensions	: 1,25 in x 1,25 in
Material	: *Polyethylene*
Thickness	: 0,14 in
PMSF	: 120 (lbs/1000 sq ft)
Size	: 6 m x 5 m for 8 sides

TABLE 6.
OFITS SPECIFICATION

Structural Type	Ocean Farm (steel)
Dimensions	diameter 16m, height 5m
Draft	1.6m
Displacement	32.89 tons
Center of gravity coordinates (Xg; Yg; Zg)	0.09m; 0.00m; -1.55m
Center of Buoyancy coordinates (Xb; Yb; Zb)	0.0m; 0.0m; -4.2m

$$x = X_i(\omega)e^{i\omega t}$$
$$RAOx = \frac{X_i(\omega)}{\varsigma_a} \quad (2)$$

$X_i(\omega)$ and ς_a represent the response and wave amplitude of the i-th motion.

I. *Time Domain Analysis*

In time domain analysis, time integration is used to generate a time history response from the time function x(t). The approach is capable of analyzing mooring rope scenarios impacted by wave frequency dynamics. Time history yields results for maximum tension, anchor loads, and additional parameters. Mooring line analysis in the time domain includes nonlinear effects such as geometric nonlinearity and hydrodynamic drag force [19]. Per DNV OS E301, time domain simulations should run for at least three hours [16].

J. *Wave Spectrum*

The wave spectrum was used to represent environmental loads such as wave load. The JONSWAP spectrum was used to simulate the waves in the open area of southern waters of Java Island. The JONSWAP equation for the wave spectrum is presented below [20] [21].

$$S(\omega) = \alpha g^2 \omega^{-5} exp\left[-1.25\left(\frac{\omega}{\omega_0}\right)^{-4}\right]\gamma^{exp\left[\frac{(\omega-\omega_0)^2}{2\tau\omega_0^2}\right]} \quad (3)$$

where α is 0,076 $(X_0)^{-0.22}$, X_0 is $\frac{gX}{Uw^2}$, X is fetch length, Uw is wind velocity, α is 0.0081 if X not determined, γ is peak parameter γ = 5 for $T_p/\sqrt{H_s} \le 3.6$ and γ = $\exp\left(5.75 - 1.15\frac{T_p}{\sqrt{H_s}}\right)$ for $T_p/\sqrt{H_s} > 3.6$, where Tp is peak period of spectrum $(\frac{2\pi}{\omega_0})$. Hs is significant wave height, τ is shape parameter (for $\omega \le \omega_o$ = 0,07 and $\omega \ge \omega_o$ = 0,09), and ω_o is frequency of wave peak $2\pi\,(\frac{g}{U_\omega})(Xo)^{-0,33}$

According to Equation 3, the peak period (Tp) for the southern waters off Java Island is determined to be 7.73 seconds, resulting in a Tp√Hs value of 5.25. The JONSWAP spectrum curve is depicted in Figure 3.

K. *Wave Directions*

The analysis shown in Figure 4 encompasses five wave directions: following seas of 0°, quarter seas of 45°and 135°, beam seas of 90°, and head seas of 180°. In following and head seas, surge, heave, and pitch motions are predominant as the waves propel the structure from the front or rear. Waves approaching from oblique or quarter angles induce sway and roll motions, impacting the structure from a cross or diagonal direction relative to its longitudinal axis [22]. In free-floating situations, vertical motions carry more intensity compared to horizontal motions.

III. Results and Discussion

A. *Results of Analysis Tensile Force on the Net*

The lumped-mass method calculates the hydrodynamics forces on a net-cage system in a fluid environment [23]. This approach considers mooring lines

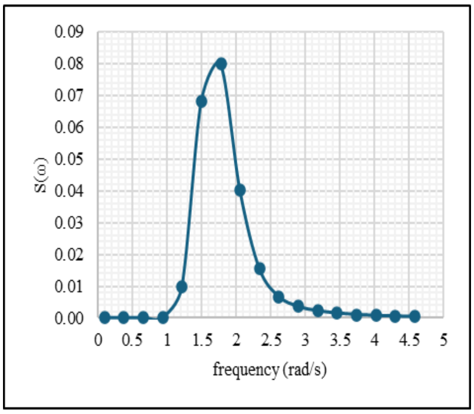


Figure 3. The JONSWAP wave spectrum in southern waters off Java Island (Hs = 2.19m, Tp = 1.78s)

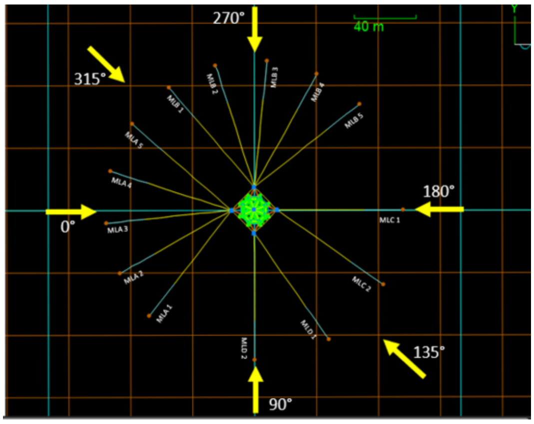


Figure 4. Wave directions

flexible ropes and divides the net cage into flat components. In this study, the net weight of the OFITS was 830 kg. The net tensile stress within the OFITS was calculated using numerical modeling based on currents and waves. The analysis indicated that the net was subjected to a tensile force of 189.95 KN due to wave and current loads at a 135° incidence angle. This force exerts a force on the OFITS mooring line. Figure 5 illustrates the net under horizontal tension from wave and current forces.

B. Results of RAO for Heave, Roll, and Pitch Motions

Figure 6a depicts the RAO values for the heave motion of the OFITS, ranging from 0 to 2.09 rad/s. The peak occurs at 1.14 rad/s with a value of 0.23 m/m and diminishes to 0.05 m/m at 2 rad/s across all headings at sea. Figure 6b illustrates the roll motion of the OFITS structure, which increases gradually in the subcritical region, rises sharply to 4.9 deg/m at resonance, and then falls to nearly 0 deg/m in the supercritical region, with the most pronounced roll motion at a heading of 90°.

In Figure 6c, the pitch motion RAO reflects the roll motion, as both are types of rotational movements. However, the primary pitch motion is observed at a wave angle of 180°.

C. Results of Structural Response

The energy density of the structure determines the structural response of OFITS due to waves. This computation of the energy spectrum of the structural motion referred to as the response spectrum, $S_R(\omega)$, is given by $S_R(\omega) = RAO(\omega)^2$ multiple wave spectrum $S(\omega)$.

Analyzing the structure's motion response in random waves relied on selecting a wave spectrum appropriate for the operational sea conditions. It concentrated on waves of extreme heights, employing the JONSWAP spectrum with a Pierson-Moskowitz modification. It considered parameters like the significant wave height (Hs) by the DnV RP C205 criteria.

$3{,}6 < Tp/(Hs)^{½} < 5$
for the Indonesia Ocean, the value
$Tp/(Hs)^{½} = 6{,}7/(1{,}86)^{½} = 4{,}905$ (qualified)

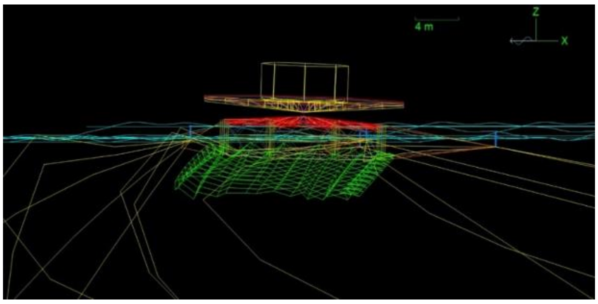
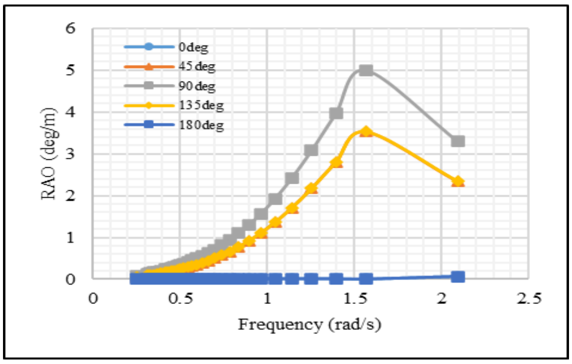
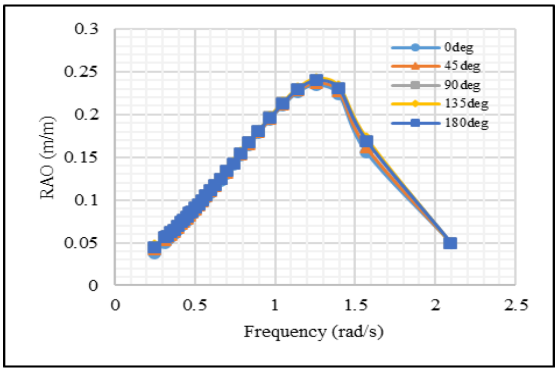


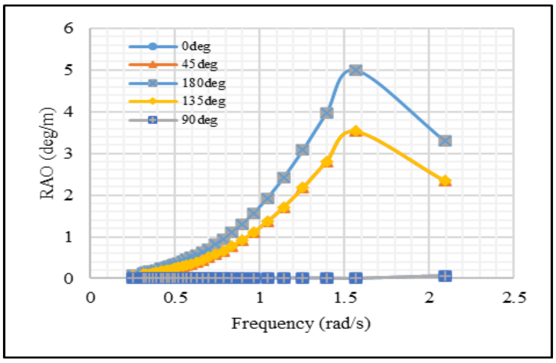
Figure 5. Net configuration



(a)



(b)



(c)

Figure 6. Motion of OFITS structure (a) Heave (b) Roll (c) Pitch

Figure 7 shows the structural response chart, which indicates the reactions across six degrees of freedom: heave, sway, surge, roll, pitch, and yaw Figure 7.

Table 7 shows the largest response of the OFITS structure under 1-year, 10-year, and 100-year wave conditions.

a) Surge Motion

For the largest surge motion in the 1-year wave with Hs = 1.86m of 0.318 [(m²/(rad/s)], 10-year with Hs = 2.24m of 0.984 [(m²/(rad/s)], 100-year with Hs = 2.35m of 1.285 [(m²/(rad/s)].

b) Sway Motion

For the largest sway motion in the 1-year wave with Hs = 1.86m of 0.317 [(m²/(rad/s)], 10-year with Hs = 2.24m of 0.982 [(m²/(rad/s)], 100-year with Hs = 2.35m of 1.282 [(m²/(rad/s)].

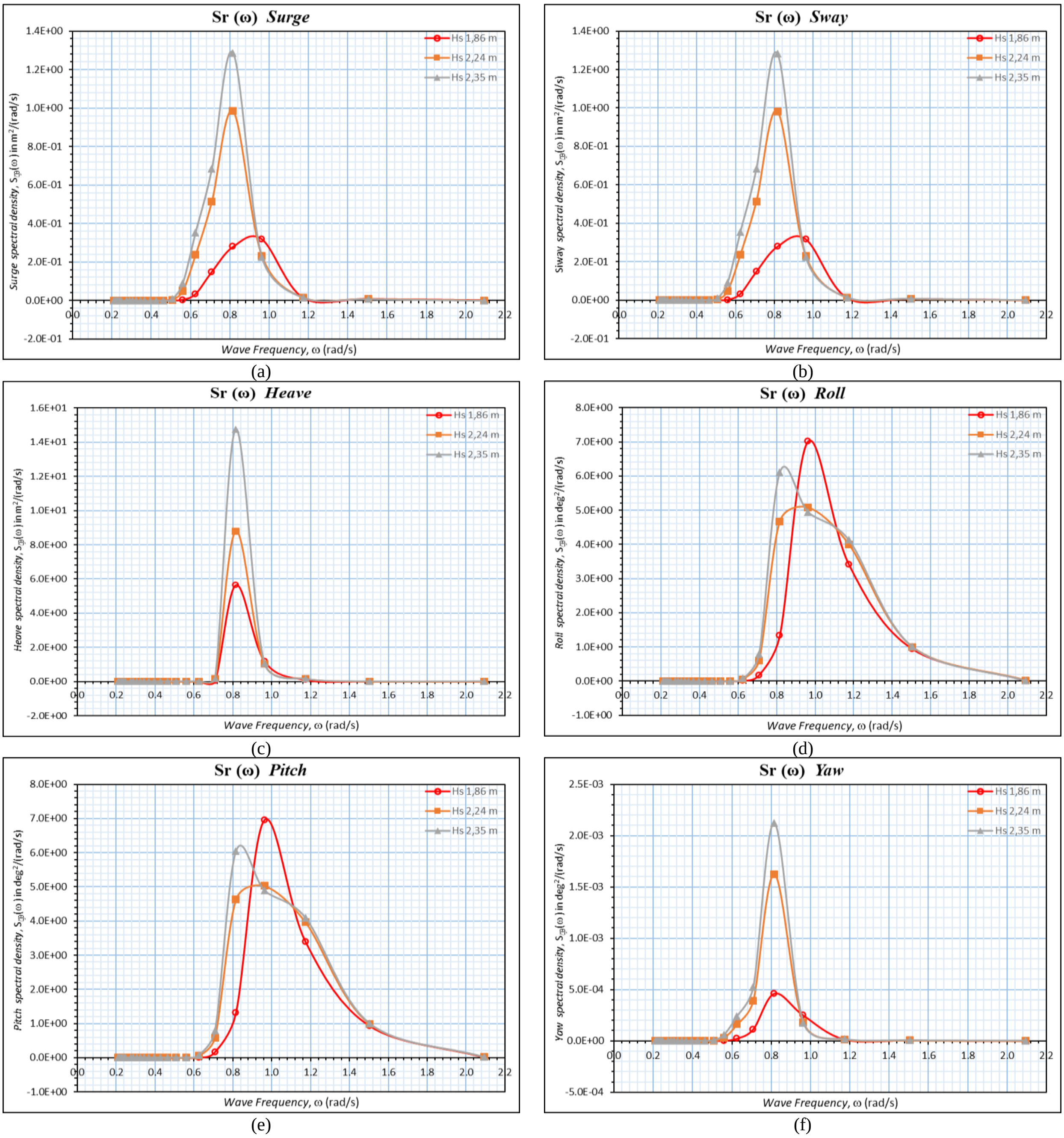


Figure 7. Motion Spectra Graph (a) Surge (b) Sway (c) Heave (d) Roll (e) Pitch (f) Yaw

TABLE 7.
SUMMARY MOTION SPECTRA

Motion	Value		
	1-year (Hs = 1.86 m)	10-years (Hs = 2.24 m)	100-years (Hs = 2.35 m)
Surge (m²/(rad/s)	0.318	0.984	1.285
Sway (m²/(rad/s)	0.317	0.982	1.282
Heave (m²/(rad/s)	5.656	8.802	14.760
Roll (deg²/(rad/s)	7.016	5.075	4.942
Pitch (deg²/(rad/s)	6.949	5.027	6.044
Yaw (deg²/(rad/s)	0.00046	0.00162	0.00212

International Journal of Marine Engineering Innovation and Research, Vol. 9(3), Sept. 2024. 495-503
(pISSN: 2541-5972, eISSN: 2548-1479)

c) Heave Motion

For the largest heave motion in the 1-year wave with Hs = 1.86m of 5.656 [(m^2/(rad/s)], 10-year with Hs = 2.24m of 8.802 [(m^2/(rad/s)], 100-year with Hs = 2.35m of 14.760 [(m^2/(rad/s)].

d) Roll Motion

For the largest roll motion in the 1-year wave with Hs = 1.86m of 7.016 [(deg^2/(rad/s)], 10-year with Hs = 2.24m of 5.075 [(deg^2/(rad/s)], 100-year with Hs = 2.35m of 4.942 [(deg^2/(rad/s)].

e) Pitch Motion

For the largest pitch motion in the 1-year wave with Hs = 1.86m of 6.949 [(deg^2/(rad/s)], 10-year with Hs = 2.24m of 5.027 [(deg^2/(rad/s)], 100-year with Hs = 2.35m of 6.044 [(deg^2/(rad/s)].

f) Yaw Motion

For the largest yaw motion in the 1-year wave with Hs = 1.86m of 0.00046 [(deg^2/(rad/s)], 10-year with Hs = 2.24m of 0.00162 [(deg^2/(rad/s)], 100-year with Hs = 2.35m of 0.00212 [(deg^2/(rad/s)].

D. Result of Mooring Tension

The OFITS mooring system's mooring line tension was analyzed using the time domain method. Simulations were conducted over three hours under extreme wave conditions, following the guidelines of DNV OS E301[16]. The mooring grid is the rope connecting the OFITS to the buoy, while the mooring line connects the buoy to the steel anchor. The results from the simulation of the asymmetric mooring line model is shown in Figure 9. The peak tension recorded on the mooring line was 18.55 tons, with a safety factor of 2.07, attributed to the line bearing a direct wave load from the sea at a 135-degree angle.

E. Discussion

An efficient mooring arrangement design is crucial for effective aquaculture projects. Offshore aquaculture systems mostly use a catenary mooring system with symmetrical mooring lines attached to the seabed. Proposed in OFITS is an asymmetric mooring line setup. OFITS uses an asymmetric mooring line arrangement with an uneven number of lines. The study proposes a unique configuration arrangement of 14 asymmetric mooring lines. Ten mooring lines were positioned at the front of the cage, aligned with the direction of the incoming waves, and four were positioned at the rear of the cage. These configurations consider both the magnitude and direction of anticipated environmental loads.

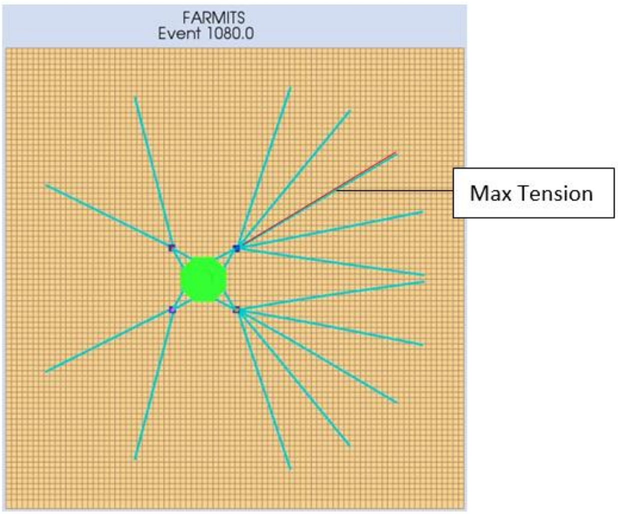


Figure 8. Location of maximum tension on mooring line

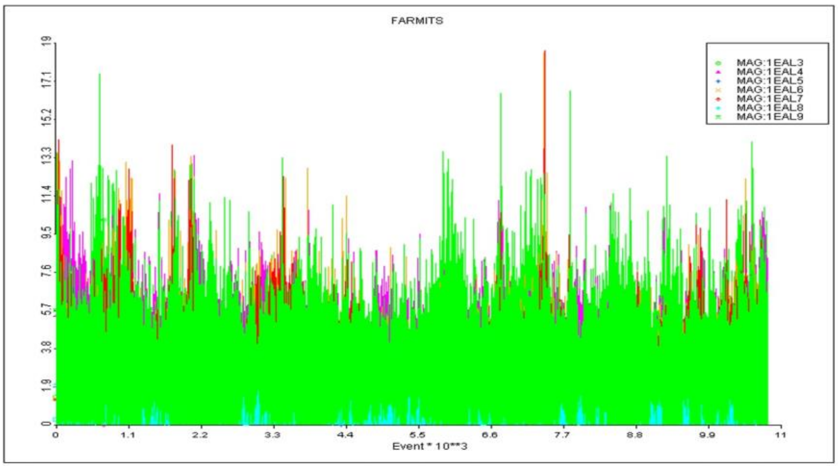


Figure 9. Result of mooring tension simulation

The lumped-mass method was suggested for conducting a net-cage force analysis in fluid settings. In OFITS, net forces can be analyzed using this method. The net experienced a 28.95 KN tensile force from waves and currents at a 135° angle, and the OFITS mooring line also experienced a force from this entity. The results offer insights into the effects of environmental load on aquaculture structures such as nets and asymmetric mooring lines.

A risk assessment study should be conducted to enhance security and progressively evaluate the most hazardous structures in each group for finite element analysis. For successful cultivation, research on the effects of stressful conditions such as acclimation, handling, and transportation on fish metabolism is necessary [24].

IV. Conclusion

This study proposed an asymmetric mooring line arrangement for the OFITS mooring system. This paper aims to examine the integrity and safety factor of an asymmetric mooring line arrangement on OFITS under an environmental load.

The OFITS asymmetric mooring line system comprises 14 lines with specified arrangements. Ten mooring lines were placed at the front of the cage, parallel to the direction of the oncoming waves, and four at the rear. In particular, the front of the OFITS faced the wave approach and had five mooring lines on its right and left sides. Two mooring lines can be found on the right and left sides of the cage near the shore.

OFITS's maximum mooring line tension was determined through time domain analysis. The nylon mooring line had a diameter of 42 mm and a minimum breaking load (MBL) of 38.4 tons. The net experienced a 28.95 KN tensile force from waves and currents. The mooring line's integrity analysis results show that the maximum tension result is 18.55 tons, with a safety factor of 2.07. It can be determined that the proposed asymmetric arrangement mooring for OFIST has good integrity and meets the DNVGL standard's safety factor requirements, with a minimum of 1.45.

Acknowledgments

The authors would like to be grateful to the ITS Surabaya Research and Community Service Directorate for financially supporting this study.

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