Analysis and Design of Offshore Aquaculture Installations

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ABSTRACT: The work starts by reviewing the current procedures for computing the loads on net structures. It proceeds to a review of the most prominent solutions available in the industry to face the challenge of offshore aquaculture developments, going also through the design considerations for this particular challenge. The feasibility of a commercially available numerical tool, SIMA, is assessed through a thorough validation process, where increasingly complex models are tested and the results compared. Then the mooring system of a real-life farm, located in the Madeira archipelago, is analyzed. The last step of this work is to combine the knowledge obtained throughout the elaboration of this thesis and propose a possible concept to be deployed in an offshore location. A hydrodynamics analysis of the concept is performed using the numerical tool SIMA.

1 INTRODUCTION

Portugal, along with other countries, as seen an increase need of supplying the market of sea products with aquaculture productions. Due to the decline of fisheries stocks and the continuously demand for sea products. This need is well expressed in the “Estratégia Nacional para o Mar 2013-2020” (Portugal, 2013), where it is considered one of the five most important domains to develop. The sea states during winter months of the continental western coast and north coast of the Atlantic islands can be very challenging. Driving a need to develop systems that could endure the harsh conditions (DGRM, 2014).

According to the latest available statistics produced by the Instituto National de Estatística (INE) (INE & DGRM, 2017), referring to the year of 2016, the majority of the national aquaculture production was molluscs and crustaceans.

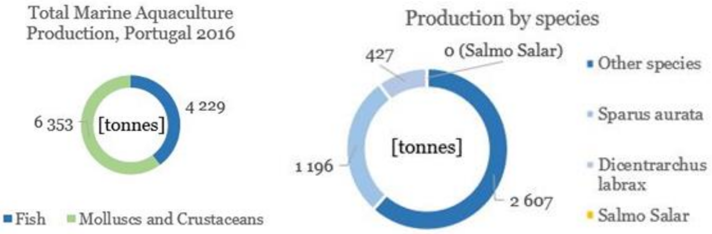

Figure 1. Portuguese Marine Aquaculture Production in 2016 (INE & DGRM, 2017)

In their publication “The State of the World Fisheries and Aquaculture” (FAO, 2018), the Food and Agriculture Organization of the United Nations (FAO) states that in 2016 the global fish production surpassed the global fisheries capture. The demand for food and feed is increasing, and the expansion of aquaculture production presents itself as one good solution. However, the growth of land and near coast aquaculture has several setbacks. Due to environmental, spatial and social restraints. Thus, the expansion of aquaculture to offshore waters is globally understood as a viable solution (Lovatelli et al., 2013).

As DNV-GL mentioned on its article (Flagstad et al., 2018) big expectations are placed on the aquaculture production and this will require an advance in knowledge, in order to fully take advantage of the offshore waters capabilities. The overall impression of my research is well expressed in the report wrote by CEA, (2018), where it is said that Norway and China are leading the development of the offshore aquaculture production, with big investments being made in the field and a lot of research as well.

2 LITERATURE REVIEW AND BACKGROUND

The above-mentioned need to move further offshore the production of sea products brings with it some challenges. Offshore structures are subjected to larger and harsher loads from the environment than coastal close structures.

These loads are caused by their exposure to waves, wind and current. Therefore, the goal to move aquaculture systems further offshore introduces the need to study and understand how these structures behave under the imposed loads and conditions. In this section a short description of the work and efforts done to model the loads on the main components of a typical aquaculture system was done.

Aquaculture systems are on its essence made by three components. A rigid, or somewhat flexible, construction that provides the structural soundness of the system and its solidity. A flexible, or in some close cage designs rigid, structure that provides a mean to imprison the fishes. Commonly through the use of a net or fabric, in a bag like fashion structure, and a mooring system to maintain the farm in a particular location. The loads on the structure and the net are crucial to the design of the mooring system. The forces on the net vary with its shape, which brings the issue of maintaining a minimum volume for the fish welfare (Shainee et al., 2013).

2.1 *Nets*

Some work has been developed on permeable structures, with an increase of research in recent years. Kristiansen & Faltinsen, (2012) defended that computational fluid dynamics (CFD) are impractical to assess the hydrodynamic forces, due to the large (in the order of millions) number of twines of a net. The same authors also say that two types of hydrodynamic force models are used: screen models and models based on the Morison equation.

Løland, (1991) proposes a wake model and a method to compute the forces on the net through the use of the drag and lift coefficients and by the division of the net in a set of panels.

$$C_D = C_D(Sn,\theta);\ C_L = C_L(Sn,\theta) \tag{1}$$

Kristiansen & Faltinsen, (2012), present a screen model, where the forces are dependent of the Reynolds number (Rn).

$$C_D = C_D(Sn,Rn,\theta);\ C_L = C_L(Sn,Rn,\theta) \tag{2}$$

This is important when validating model tests. This screen approach discretizes the net in a series of surface elements, whose properties reflect the twine and knot geometry of the actual net. In this screen model approach the drag and lift coefficients depend on the solidity ratio (Sn), angle of attack (θ) and the Reynolds number (Rn).

The Morison based approach implies the subdivision of the net in a smaller number of twines, in the form of cylinders, in such a way that the projected area is kept the same. A model where the drag and lift coefficients depend on the Reynolds number (Rn) is used by Le Bris & Marichal, (1999) on their work on the behaviour of submerged nets, and by (Moe et al., 2010; Tsukrov et al., 2002).

A super-element model was proposed by Lader et al., (2001), where the net is divided in small patches of four-sided super elements. The forces are computed through the Morison equation and the drag and lift coefficients are dependent on the Solidity ration (Sn) and angle of attack (θ), the Reynolds number (Rn) is not explicitly accounted for. This dependency of Sn and θ is also the base of the work of Aarsnes et al., (1990), later refined in the model of Løland, (1991)

On their paper Le Bris & Marichal, (1999) pointed out that the hydrodynamic interactions between mesh sides are not taking into account. This is also referred by Kristiansen & Faltinsen, (2012) as one of the objections to the Morison based approach. The objections are namely: each twine does not influence the adjacent ones, meaning that “shading effect” and velocity changes due to decrease in projected area for each twine are not accounted for; for inflow angles larger than 45°, the drag force computed is exaggerated.

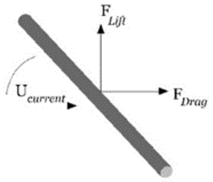

Figure 2. Lift and drag forces on a twine in a uniform current

2.1.1 *Empirical Loads on Nets*

From the towing tests of Rudi et al., (1988), three authors (Aarsnes et al., 1990) derived an empirical formulation for the hydrodynamic forces on stiff net panels under uniform flow. This method, that could be used for a preliminary assessment of loads, is limited for the range of solidity ratios (Sn) and Reynolds number (Rn) of the towing experiments, where the Reynolds number is based on the twine diameter. As a result, the empirical formulas proposed do not account for the drag and lift coefficient Reynolds number’s dependency (Lader & Fredheim, 2006).

On their work, Lader & Enerhaug, (2005), compared the hydrodynamic forces computed with the empirical formulas of Aarsnes et al., (1990), eq. (3) and (4).

$$F_D = \frac{1}{2}\rho C_D A U^2 \tag{3}$$

$$F_L = \frac{1}{2}\rho C_L A U^2$$

$$C_D = 0.04 + (-0.04 + 0.33S + 6.54S^2 - 4.88S^3)\cos\alpha \quad (4)$$

$$C_L = (-0.05S + 2.3S^2 - 1.76S^3)\sin 2\alpha$$

and measurements of a model test.

According to them, the use of direct formulas for computing the global hydrodynamic forces on net cages overestimates the forces (the lift force is not shown, but a similar phenomenon occurs). Mainly because these empirical formulas do not take into account the net deformation and change of geometry. The presence of the attack angle of the net in the formulas of the drag and lift coefficient implies a high dependency between the drag and lift force on the net and its geometry.

2.2 *Structure*

The majority of the work done in the analysis of fish farm behaviour under loads was performed for floating collar structures. Since those have been the standard in the industry for a long time. As referred by Li et al., (2017) the responses of these structures are usually done by means of a strip theory analysis, and the drag force included via Morison equation. However, it is remarked that 3D frequency-dependent interactions and hydroelasticity effects are not accounted for in a 2D analysis. Since these effects are of major importance, the same authors proposed a beam model to compute the motions of the floating collar Such an approach was also previously done by Li & Faltinsen, (2012).

As seen before, the emerging designs for offshore locations differ from the traditional floating plastic collar and become more similar to floating rigs and vessels. Therefore, the same procedures used for these structures can be applied, with the added complication to include the forces caused by the net cage. As clearly stated by Chakrabarti, (2005) the method to compute loads on floating structures depend on their size relative to the wavelength. For slender structures normally the Morison equation is used to computed wave and current's loads. For larger structures a diffraction and radiation linear analysis is used.

2.3 *Mooring*

Mooring systems are used to maintain the structure in the desired place against waves, current and wind, by reducing its horizontal offset. Two systems are traditionally used, taut and catenary configurations. More on this further on. From my findings, I got the impression that the modelling of the mooring lines was mainly dictated by the software tool chosen. Shen et al, (2018) use elastic trusses, with adequate weight and stiffness, to model the mooring lines. And the forces computed by Morison equation. Other approaches have been adopted, (Bore & Fossan, 2015) used tubular beam elements to model the mooring lines due to limitations of the software employed.

Two approaches are taken regarding mooring analysis: uncoupled and coupled. The uncoupled analysis is recognized to be simpler and faster, and the coupled to be more accurate, although more time consuming.

The uncoupled analysis consists in computing the floating body motions and then, in a second analysis, imposing these motions as conditions at the end of the mooring system. The drawbacks of this analysis are the failure to incorporate the damping effect (on the low frequencies motions of the body) and current loads of the mooring system, and not accounting with the influence of the mooring system in the body wave frequency motion. These drawbacks gain more importance as the depth of the system increases. In a coupled approach, the motions and loads of both the floating body and the mooring system are solved for each time step. Therefore, the interaction between the two is considered. For a coupled analysis regularly a non-linear time domain method is used, aiming for equilibrium at each time step (Jo et al., 2013).

3 VALIDATION

The chosen software for the analysis of a fish farm was SIMA- Simulation Workbench for Marine Applications (SIMA) by DNV-GL. The software is a well-established and trusted commercially available tool.

The validation was done in five stages. One with the analysis of Moe et al., (2010) a second with the numerical analysis of Li e al., (2011), a third with the work of Zhongchi Liu at CENTEC , the fourth was a joint work with Sarat Mohapatra at CENTEC as well, and the last with the results of the numerical software FhSim, provided by SINTEF. Some analysis uses more complex systems than others, the criteria for their choice was mainly due to their strength as good sources of results and the possibility of emulating their models in the SIMA platform.

4 CASE STUDY

On the south side of Madeira island there is an aquaculture farm for the production of gilt-head bream (*Sparus Aurata*) with around 20 cages on a site approximately 0.5 nautical miles from the coast.

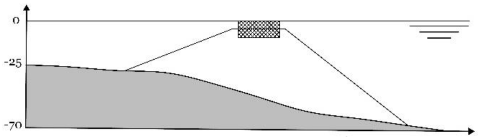

Figure 3. Top and cross section of 3D bottom model

The ocean floor geometry of the site was replicated as possible, so the mooring system model is closer to the real one deployed.

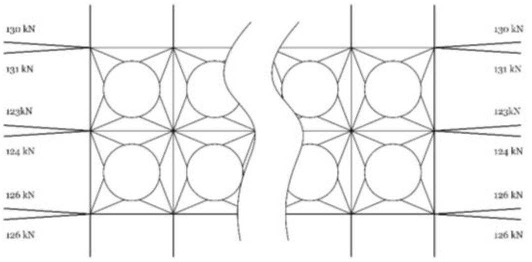

Figure 3. Mooring lines pre-tension force

A review of the mooring system of the farm was conducted. An analysis of the implemented system was performed, with a 40 year long wave data record, collected in situ and provided by the company.

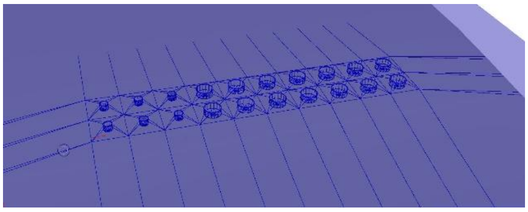

Figure 3. 3D model built in SIMA of Madeira's system

5 DESIGN

One of the key parameters for the design of an aquaculture system is the fish demands, with each species having its own requirements regarding temperature, oxygen levels, salinity, among others (Shainee et al., 2013). Although the perfect levels of this requirements might not be known for the farmed species, adequate levels have been found through experience and studies (Pillay, 1992).

The concepts and designs developed for offshore locations are sourcing a lot of knowledge from the offshore oil and gas industry. Reason why a certain resemblance is visible between rigs and some of the emerging design solutions. Nonetheless, some interesting solutions are being pursued such as vessel shaped farms and close cage systems.

- ***Close Cage***

In a closed system, a better control over the fish environment exists, with a better management of the water flow and quality. In addition, an improved handling of the fish waste is possible. Therefore, reducing the environmental pollution. Being a close structure exposed to sea loads and having a free surface, this system will have sloshing inside. The structure can be flexible or rigid. If flexible, then the deformation due to loads will affect the hydrodynamic behaviour of the structure.

- ***Vessel Shape***

The two known designs of a vessel shaped cage differ from each other, but on its essence, they are a vessel shaped floater divided in multiple cages and making use of a single-point mooring (SPM) solution. As well described by Li et al., (2017). This choice of mooring aims to allow the farm to position itself in a favourable position when facing waves and currents.

- **Rig Type**

As mentioned before, one of the strategies to tackle the offshore environment challenges is by seeking knowledge and solutions from the offshore oil and gas industry and adapting it to the aquaculture needs (Bore & Fossan, 2015). These designs are made of a series of joint beams, sometimes forming a truss like structure.

From the research carried out for this thesis it can be said that the rules and standards for offshore aquaculture production systems are still on their beginnings.

A Norwegian technical standard is already in place and used for aquaculture systems, the NS 9415. On 2017 DNV-GL came forward with a document stating the rules for classification of offshore fish farm units (DNVGL-RU-OU-0503).

The desired class notation for offshore fish farming installations is the OI notation. This notation applies for non-self-propelled fish farming installations, deployed at a given location for an extended period, in conformity with all the offshore standards of the classification society.

In the design process the requirements or each stake holder should be identified. According to Shainee et al., (2013) the requirements for the fish, farmer and society hold the biggest importance in the design of an aquaculture system.

For the fish, the parameters are mainly biological. Such as: salinity, temperature, pollution, stocking density, among others. The water motion and available cage volume are also important.

For the farmer, the system should provide good accessibility conditions and allowed tasks such as: feeding, harvesting, treatment, etc. to be performed. It should also provide good conditions for monitoring, whether through a clear water visibility or through installed monitoring technology, or both.

For the society, the production system should have a low environmental impact, with low pollution, low escapes and a small impact on the ecosystem. It should be a good source of employment, income and provide good quality produce.

Shainee et al., (2013) make a very interesting review and categorization of different concepts. It proposes two categories, based on the ability of the system to endure the external conditions. In each category a subdivision is done, with respect to the strategy employed. The categories are:

- *Designed to withstand and dissipate the loads:*
  - Floating rigid
  - Gravity net cages
- *Designed to avoid the loads*
  - Submerged
  - Submersible

6 RESULTS

The results of the validation process, case study and concept proposal provided some insights of the feasibility of the chosen software, SIMA, in the design stage.

6.1 *Validation*

It was concluded that this software is not the best tool to analyze the behavior of a free hanging net. As can be seen by the results, there are some discrepancies between the experimental net behaviors and the ones predicted by the software. One major cause of these might be the way the software represents a net panel, through an equivalent single vertical cable/bar element. This of course does not consider the physical linkage between two twines. Another important point is the influence of each twine in the flow of the others. The wake effect is not properly modelled in the SIMA software, which may lead to higher loads on the net elements located downstream and an overall increase of the cage load (Aksnes, 2106). Although there is the possibility to set the velocity reduction factor for each net element, it remains constant throughout the simulation. When ideally it should be adjusted with the changing position and angle of the elements.

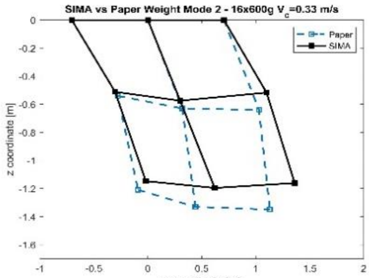

Figure 4. Side view comparison, numerical vs SIMA results

Therefore, for a more detailed analysis of the net geometry a numerical tool with a more complex description of the equivalent net element should be used, but this work is focused mainly on the forces caused by the environment onto the net cage. The suitability of this tool for this purpose was backed up by the results, which lead us to state that the global forces on the net cage were being reasonably computed, to a certain extent. Therefore, the results of these validation processes suggest that the chosen software SIMA is a good tool to perform an assessment of the loads on a fish farm system and its mooring systems.

6.2 *Case Study*

The intention was to verify the design of the installed mooring system, making use of the proposed numerical tool and method, by evaluating the mooring system with a Ultimate Limit State (ULS) analysis, through the computation of the utilization factors (u) for each condition, as advised by DNV-GL The utilization factor is a ratio between the load on the cable and its characteristic strength (DNV-GL, 2015).

$$\boldsymbol{u} = \frac{\boldsymbol{T_{c-mean}\gamma_{mean} + T_{c-dyn}\gamma_{dyn}}}{\boldsymbol{S_C}}, \boldsymbol{u \leq 1} \tag{5}$$

Table 1. Mooring lines utilization factors, u<1

	W. Line 2	W. Line 4	W. Line 6	E. Line 2	E. Line 4	E. Line 6
WC1	0.53	0.63	0.52	0.32	0.31	0.35
WC2	0.52	0.62	0.51	0.33	0.34	0.35
WC3	0.58	0.83	0.60	0.38	0.48	0.42
WC4	0.61	0.87	0.65	0.37	0.48	0.45

In addition, the long-term probabilities of exceedance of the mooring lines are also computed.

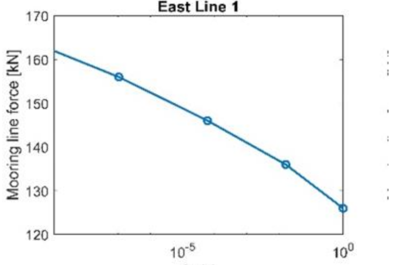

Figure 5. Long term probability of exceedance of mooring line axial force

The results showed that the current mooring system satisfies the class requirements regarding the ULS capacity of the lines. Although it is important to remark that this analysis was done for one single current velocity and direction. A full evaluation of this aquaculture mooring system would require a much more thorough analysis. Thus, such analysis is thought to be out of the scope of this work, that intended, among other things, to demonstrate the feasibility of the numerical tool SIMA in the analysis of this kind of structures.

6.3 *Design Proposal*

The concept proposed in this work is a submersible cage shaped in a hexagonal prism. With an outer rigid structure composed by two circular rings connected by rigid columns members

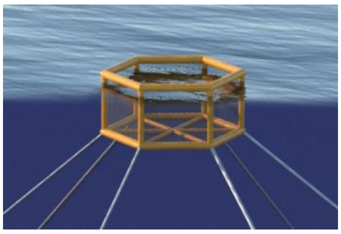

Figure 6. Concept Proposal of a 765 m3 cage

A hydrodynamic analysis of the concept was performed. Firstly, the RAOs (Response Amplitude Operators) of the cage itself (structure plus net) are computed. Thenceforth, the RAOs of the cage plus mooring system are recomputed. In this way a brief comparison is made between the two conditions.

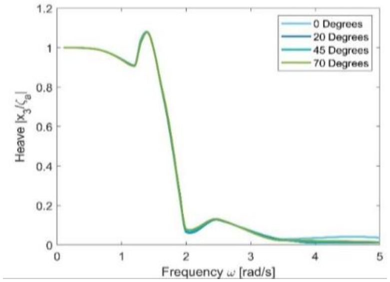

Figure 7. Non-moored structure RAO for heave motion

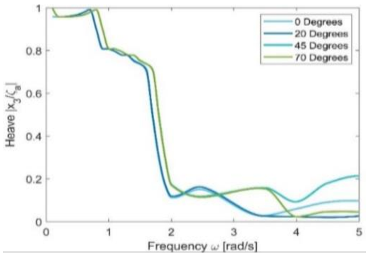

Figure 8. Moored structure RAO for heave motion

Because the structure does not have suspended nets, all net panels are attached to the structure at their boundaries (non-deformable), the current loads on the cage should be significant To access this, a study of the axial force of the mooring lines was performed for different current velocities (without waves). Moreover, the computation of the overall current induced drag force on the cage is also computed.

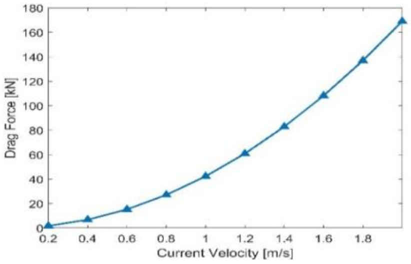

Figure 9. Cage's drag Force due to current, orientation of 0º

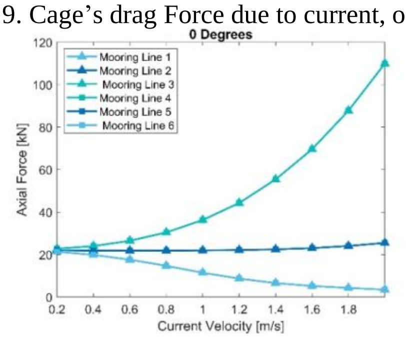

Figure 10. Axial force of mooring lines under different current velocities

7 CONCLUSION

The purpose of the present work was to launch the interest for the aquaculture sector, more specifically the offshore, in our marine department and lay off the foundational work for further research. This was done through the formulation of the design criteria, identification of environmental constraints and the proposal of a numerical tool to assist in the study of the main components during the design process. It ended with the analysis of an existing system and the design, plus analysis, of a new system concept.

Using the knowledge gained throughout the elaboration of this work, a rough analysis was done to an existing system. The analysis was simple enough and the tool coped well with the size and complexity of the system, strengthening the point that this tool can be an aid in the design process.

Lastly, making use of the criteria and requirements discussed, a basic design concept was introduced. The main point was to illustrate the role that the different criteria and requirements had in each design decision and how the SIMA tool could be used for an initially assess of the loads and help the mooring design. SIMA proved to be a very useful tool due to its in-built fish net element, that simplified the design and analysis. Although, there is a downside. It is a very time-consuming task, due to long computational times and required post treatment.

The most important lesson from this process being the weaker performance of the tool, when compared with other codes, to access the net behavior in a detailed way. Although it performed well in the assessment of the loads onto the nets. This two main observations can be summarized in a recommendation: this tool is not the best for a more academic study of the net behavior, such as the sensitivity to different parameters or predicting the net shape, but it is a good choice for the study of more complete systems, where the focus is in the behavior of the cages and its complementary elements, such as moorings. Ideally this tool should be used in association with experimental trials, in such a manner as to allow a good tuning of the model.

8 FURTHER WORK

It would be interesting to perform comparison analysis between the SIMA tool and other tools of the SESAM package, such as HydroD. In order to access if it is viable to use them for some parts of the analysis, the computations of the RAO for example, in a way to create a more efficient workflow in the analysis of these aquaculture systems. To improve the SIMA model building procedure, a series of experiments with model tests could be performed so a deeper knowledge of model tuning within the software could be achieved.

9 ACKNOWLEDGMENTS

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