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**PREDICTING THE HEADING MISALIGNMENT OF A VESSEL-SHAPED OFFSHORE  
FISH FARM UNDER WAVES AND CURRENTS**

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**ABSTRACT**

*A vessel-shaped fish farm concept for open sea applications has been proposed recently. The whole system consists of a vessel-shaped floater, fish cages positioned longitudinally along the floater, and a single-point mooring system. The whole system weathervanes; this feature increases the spread area for the fish waste. However, the downstream cages may experience reduced water exchange when the vessel is parallel to the currents. This situation may jeopardize the fish health. A dynamic positioning (DP) system may be necessary to improve the flow conditions. This paper investigates the misalignment angle between the heading of the vessel-shaped fish farm and the currents under combined wave and current conditions. The misalignment angle is critical for the estimation of the DP system consumption. A numerical model of the fish farm system with flexible nets is developed. Current reduction factors are included to account for the flow velocity reductions between the net panels. The heading of the system is obtained by finding the equilibrium condition of the whole system under each combined wave and current*

*condition. An integrated method using metamodels is proposed and applied for the prediction of the misalignment angle for a reference site. The probability distribution of the misalignment angle between the vessel heading and the currents is calculated using the Kriging metamodel for the reference site. Based on the prediction, the requirement for the DP system to improve the flow condition in the fish cages is discussed.*

**INTRODUCTION**

There are many benefits of installing fish farms in exposed seas, including ample space for expansion, tremendous carrying capacity of sea water, reduced conflict with many user groups, lower exposure to human sources of pollution and the potential to reduce negative environmental impacts. However, the development in offshore waters is facing significant technical and operational challenges due to harsh environmental conditions. Fish farming in fully exposed offshore areas requires new engineering approach since equipment and methods currently used in protected nearshore areas are mostly unsuitable for open seas [1]. Therefore, novel and robust offshore fish farms are

required to meet the challenges.

Several new and potential fish farm concepts for open seas have been recently proposed in the Norwegian aquaculture industry. Until the end of 2017, five concepts had been granted development licenses from the Directorate of Fisheries in Norway. The five concepts include two closed concepts, one semi-closed concept and two open cage offshore fish farms. One open cage design, the semi-submersible fish farm ‘Ocean Farm 1’ developed by Ocean Farming AS, is the world’s largest offshore fish farm [2]. The design combines the technology from the fields of the aquaculture and offshore oil and gas industry. The pilot facility has been installed off the coast of central Norway in 2017 [3]. Norway Royal Salmon AS and Aker Solutions ASA proposed another semi-submersible fish farm, and the global response analysis of a similar structure under waves has been carried out in both frequency and time domains [4].

Another open cage fish farm is the vessel-shaped fish farm named ‘Havfarm’ proposed by Nordlaks AS; see Fig. 1. The concept consists of several cages along the longitudinal direction of the vessel. Two different ‘Havfarm’ concepts using different positioning systems were suggested from Nordlaks: the stationary and the dynamic farms. The stationary farm is positioned using a passive single point mooring system connected at the bow of the vessel. Thus, the heading of the whole farm will be determined by the wind, wave and current loads and directions. The proposed dynamic ‘Havfarm’, on the other hand, will not have a permanent mooring system, but mainly rely on the dynamic positioning (DP) and propulsion systems to maintain its position and to relocate. The energy consumption as well as the operational and maintenance cost may increase substantially compared to the stationary farm.



**FIGURE 1:** Overview of the vessel-shaped fish farm concept [5].

This paper addresses numerical study of a vessel-shaped fish farm, which is modified based on the design of the stationary ‘Havfarm’ as shown in Fig. 1. Global response analysis of this structure in combined currents and waves has been carried out in our previous publications [6, 7]. The whole fish farm

is a weathervaning unit and allows the structure to head to the currents and waves under most conditions. In such situations, the downstream cages may experience reduced water exchange compared to the upstream cages due to the shielding effects since the whole farm consists of several cages in a row with small distances in between.

In reality, the water flow in and around the open fish cages is complex and affected by several factors, including the physical properties of the cage structure [8], bathymetry [9], farm organization [9] and the movement of the fish themselves [10]. Extensive investigations, both numerically and experimentally, have been carried out in recent decades to understand the flow fields of a net cage, examples of the studies can refer to [11, 12]. Although the local flow conditions around the nets are complex and three-dimensional, these studies generally revealed that water motion helps to maintain the water quality in a net cage and sufficient water exchange is important for the health and growth of the fish.

From operational point of view, to improve the water exchange, one good solution is to rotate the whole structure to be misaligned with the current direction. So, the shielding effects from the upstream cages can be mitigated. To realize this, in practice, a DP system with thrusters may be necessary to counteract the environmental loads and to change the heading of the structure. Because of the high energy consumption, it is important to estimate the power required of the DP system in the design phase. The DP power consumption can be calculated based on the target misalignment angle between the structure and the currents, which is assumed to be a good indicator for the flow conditions in all the cages.

Thus, the focus of this paper is to investigate the misalignment angle between the heading of the vessel-shaped fish farm and the currents under realistic environmental conditions using a passive single-point mooring system. The purpose is to provide useful information for design of the DP system to improve the flow condition in the fish cages. A numerical model of the coupled fish farm system, including the vessel, the flexible fish cages and the mooring system is firstly developed. Then, an integrated method using metamodels is proposed and applied for the calculation of the misalignment angle for a reference site. Irregular deep-water waves and uniform currents are assumed in the analysis. The probability distribution of the misalignment angle for this site is predicted. By using a simple estimation of the current reduction factor inside each cage, the requirement for using the DP system to improve the water exchange is discussed.

## **DESCRIPTION OF THE VESSEL-SHAPED FISH FARM**

The whole fish farm consists of a vessel-shaped floater, five flexible fish cages, and a mooring system. In our study, we used a simplified floater design compared to ‘Havfarm’ to simplify the analysis. The floater consists of a bow, two main

longitudinal support beams, and transverse beams to strength the main support beams. In normal operational conditions, only the bow and the longitudinal beams are submerged. This provides a large opening area for the cages. Steel louse skirts are designed to isolate the fish from the currents in the upper layer to reduce possible influences of sea lice [5].

The main set-up of the concept and the dimension of the submerged part of the vessel is illustrated in Figure 2. The structure has a total length of 400 m, a breadth of 50 m and a draft of 10 m. Five cone-shaped cages are connected to the floater at 10 m below the mean water surface. Each cage has a 48 m diameter at the top and a depth of 50 m. A bottom weight of 4 tonnes is used under each cage to tension the net and maintain the volume of the cage. The material properties of the fish nets are shown in Table 1. The solidity ratio of the nets, which is defined as the ratio of the projected are of the net over the total area, is chosen as 0.2.

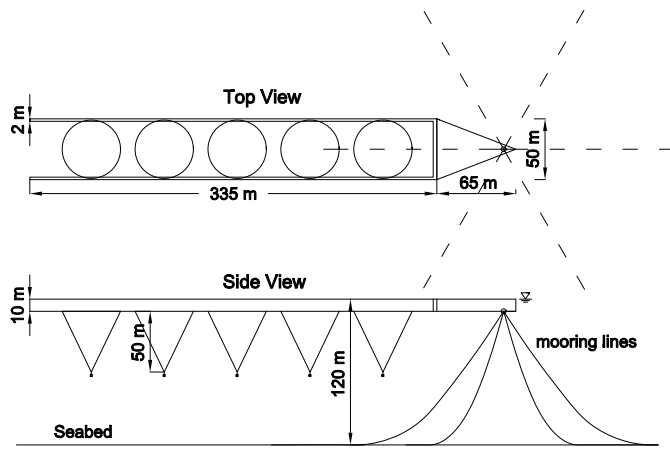


FIGURE 2: Main geometry of the submerged part of the vessel-shaped fish farm.

TABLE 1: Properties of the fish nets

Solidity ratio	[-]	0.2
Twine thickness	[m]	0.005
Density	[kg/m <sup>3</sup> ]	1120
Elastic modulus	[MPa]	900

A single-point mooring system consisting of six mooring lines with 60 degrees spacing in between is proposed. The mooring lines are connected to the turret located at the bow; see Figure 2. Such a configuration allows the vessel to weathervane

passively with minimal stress on the mooring system. Under extreme environmental conditions, the turret can be efficiently disconnected from the vessel, making it possible for the whole fish farm to move to a sheltered area.

Each mooring line is composed of four segments, including a chain segment, a wire rope segment, and two links between the segments and the fairlead. The chain segments provide adequate restoring forces when the horizontal displacements of the turret are large. The length of the wire ropes should be adequate to avoid possible contact with the seabed under mean drift and dynamic responses. The geometry of the mooring lines does not interfere with the cone-shaped fish cages during motion. The detailed properties of the mooring line components can refer to Ref. [7]. The total length of each mooring line needs to be adjusted based on the water depth of the selected site.

## NUMERICAL MODEL

The coupled numerical model of the fish farm, including the floater, the flexible nets and the single-point mooring system, has been established using SIMA (SIMO and Riflex) program developed by SINTEF Ocean [13–15]. SIMO models the rigid body hydrodynamics of the floater structure and Riflex models flexible elements for the fish nets and the mooring lines using finite element methods. Figure 3 presents the top view of the coupled numerical model. The global coordinate system (with origin at the turret center), definition of the wave and current directions, and the cage and mooring line numbers are also shown. The modeling considerations as well as the theoretical background are briefly discussed as follows.

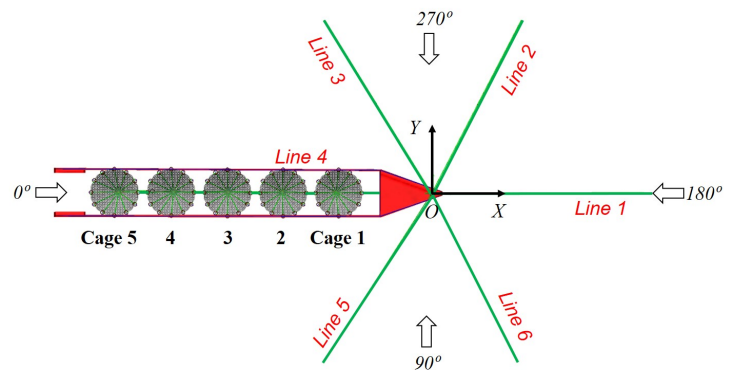


FIGURE 3: Illustration of the coupled fish farm model with global coordinate system and mooring line numbers

## Hydrodynamics of the floater

The hydrodynamic properties of this vessel-shaped fish farm concept were obtained in the frequency domain. A first-order

panel model was generated in the Wadam program [16]. Linear potential theory was applied across relevant wave frequencies. Ref. [6] presented the added mass, damping and response amplitude operators (RAOs) of the fish farm for various models with and without rigid net elements. It was shown that the addition of the nets contributes significant viscous damping to the rigid body motions of the floater. The RAOs of the floater were greatly reduced when including the nets, in particular with a higher solidity ratio.

In this paper, the mean drift wave forces on the floater are used in the calculation of the static equilibrium of the whole structure under waves and currents. Moreover, additional viscous damping in terms of Morison elements have been added on the support beams and the bow of the floater. The viscous damping on the triangular shaped bow was modeled using three beams on the edges of the triangular. Equivalent drag coefficients on the beams in vertical and horizontal directions were selected based on the two-dimensional coefficients from DNV recommended practice [17].

### Modeling of flexible nets

The fish nets are flexible structures, and the cages will experience different degrees of deformation depending on the wave and current conditions. The drag and lift forces of the net elements changes with the deformation. In the numerical model, each cage is divided into 12 net panels circumferentially. Each net panel is then represented by a slender line consisting of bar elements, as shown in Fig. 4. Equivalent properties of the twines within the net panel are calculated based on the input using Table 1 and applied to the bar elements, including mass, volume and axial stiffness. The drag ( $F_D$ ) and lift ( $F_L$ ) forces on a net panel are calculated as:

$$F_D = \frac{1}{2} \rho C_D A U^2 \quad (1)$$

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

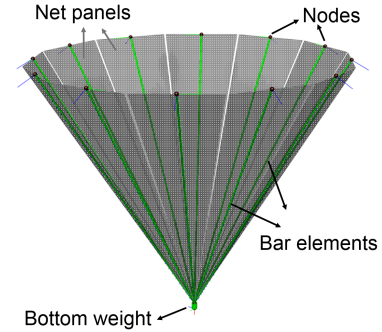
where  $\rho$  is the water density,  $A$  is the area of the net panel,  $U$  is the total flow velocity, including current and wave induced fluid velocities. In the present model, the hydrodynamic drag and lift coefficients of the net panel,  $C_D$ ,  $C_L$  are empirical coefficients based on model test data [18].

$$C_D = 0.04 + (-0.04 + 0.33S_n + 6.54S_n^2 - 4.88S_n^3) \cos\theta \quad (3)$$

$$C_L = (-0.05S_n + 2.3S_n^2 - 1.76S_n^3) \sin 2\theta \quad (4)$$

where  $S_n$  is the solidity ratio of the net panel. The angle of attack,  $\theta$ , is defined as the angle between the flow direction and the

normal vector to the net panel in the direction of the flow. Under different environmental conditions,  $\theta$  of each bar element will change due to deformation of the net panels, and the total drag and lift forces will change accordingly. The above empirical are limited to  $S_n$  ranging from 0.13 to 0.32 [19].



**FIGURE 4:** The flexible fish net model using representative bar elements.

### Current velocity reduction factor

Due to the loss of momentum when water flows through a net panel, a continuing reduction of flow velocity occurs in the downstream cages. This is especially important for the present concept where several net cages are positioned in a row. Here we define the current reduction factor,  $R$  as follows:

$$R = 1 - \frac{u_i}{U_\infty} \quad (5)$$

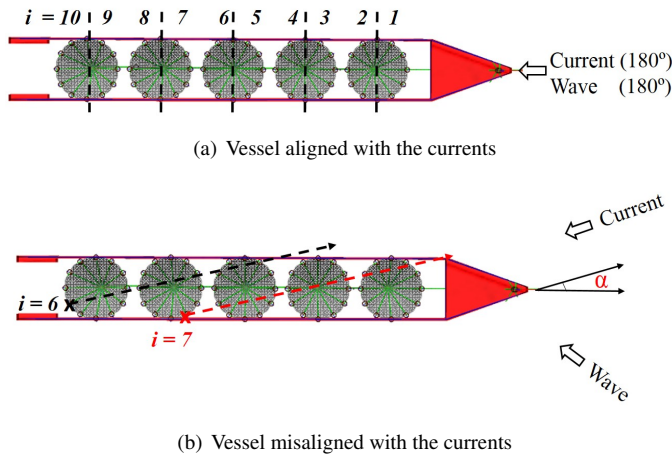
where  $U_\infty$  is the incoming current velocity.  $u_i$  is the local current velocity felt by the  $i^{th}$  net panel facing the flow. In reality, the flow around the net structures is complex and three dimensional. The flow may be partly redirected due to the resistance of the nets, biofouling and motion of the fish [8]. All these factors will influence the local current velocity,  $u_i$ , and its direction. However, in this study we assume uniform flows before and after passing the net panels and apply the simple engineering approach suggested by Løland [18] for calculation of the local velocities on the net panels.

$$u_i = U_\infty \cdot (1 - R) = U_\infty \cdot (1 - r)^{i-1} \quad (6)$$

$$r = 0.46 \cdot C_D \quad (7)$$

where  $r$  is the current velocity reduction factor behind one net panel.  $C_D$  is the drag coefficient on the net panel, and it depends on the solidity ratio  $S_n$ ; see Eq. (3). For a given  $S_n$  ( $S_n = 0.2$  in our case) with the corresponding  $C_D$ , the local current velocity,  $u_i$  at each net panel only depends on the value of  $i$ . The value  $(i - 1)$

indicates how many times of reduction the net panel experiences. For the vessel-shaped fish farm consisting of five fish cages, different net panels on the same cage may experience different current reductions, depending on the position of the net panels and the relative current directions. The calculation of the  $i$  values for different conditions are illustrated in Fig. 5



**FIGURE 5:** Illustration of the calculation of  $i$  values in Eq. (6) for reduced current velocity under two conditions.

When the currents and waves are aligned, see Fig. 5(a), the vessel will position itself heading to the currents (both current and wave directions are 180 degrees). Because each cage consists of the front and rear parts,  $i$  from 1 to 10 are used for corresponding net panels from Cages 1 to 5.

Under misaligned conditions, there will be a certain misalignment angle,  $\alpha$ , between the heading of the vessel and the current direction in the equilibrium position, as shown in Fig. 5(b). The local current velocity at the net panels along one cage will be different, depending on the shielding effects from the nets in the upstream. The following method is proposed to find the  $i$  values for the calculation of the current velocity reduction. First, an artificial line is drawn from each net panel (modeled as slender line with bar elements) parallel and opposite to the current coming direction. Second, the intersections of the line are found with the other cages in the upstream of the net panel. Each intersection accounts for one time of shielding. Finally, the  $i$ -value corresponds to the total number of intersections. Two examples are given with  $i$  values equal to 6 and 7 respectively in Fig. 5(b).

It should be noted that, the velocity reduction calculated here is only for the pure current velocities. The water particles move in circles in waves with radius equal to the wave amplitude at the free surface. This radius decays quickly with water depth. Thus,

the reduction of wave particle velocities is considered secondary compared to the current reduction.

### Iterative routine for calculation of static equilibrium

Because the current reduction depends on the relative angle between the vessel heading and currents,  $\alpha$ , an iterative routine is proposed below to find the static equilibrium of the vessel-shaped fish farm under any combined wave and current condition.

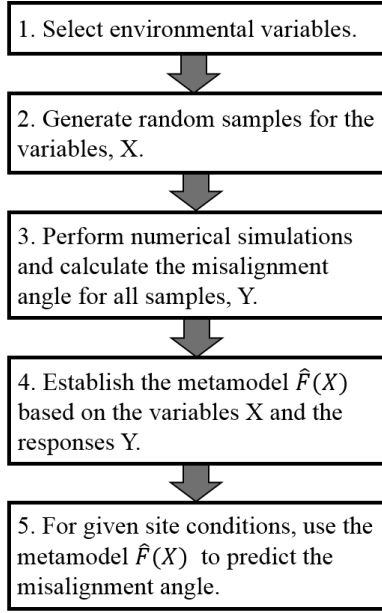
1. Assume the initial value  $\alpha_0 = 0$ , so the current reduction can use the one shown in Fig. 5(a).
2. Run static analysis of the coupled numerical model under given wave and current condition. New equilibrium can be found and a new misalignment angle  $\alpha_k$  is obtained.
3. Update the current reduction factor on each net panel of each fish cage based on  $\alpha_k$  and the proposed method shown in Fig. 5(b).
4. Repeat the previous two steps and obtain a new  $\alpha_{k+1}$ . The iteration continues until the difference between  $\alpha_k$  and  $\alpha_{k+1}$  is within the tolerance ( $10^{-1}$  degrees).

### INTEGRATED METHOD USING METAMODELS

#### Integrated method

This study aims to predict the misalignment angle between the vessel and the currents for any site condition. To provide an accurate estimation for a specific site, long term environmental description with wave and current hindcast or measurement data over many years should be used. However, to perform numerical simulations for all the conditions over many years will require significant computational time, and will not be feasible. Thus, approximation techniques can be applied to minimize the computation expenses. The basic approach is to approximate the computationally expensive simulation codes with surrogate models, which can be sufficiently accurate to replace the original code. The surrogate models are often called metamodels. Metamodels are popular engineering tools to minimize the computational costs and have been applied in many fields, such as design optimization and reliability assessment [20–22].

In this paper, an integrated method using metamodels is proposed for the prediction of the misalignment angle between the vessel and the currents for any site condition. The integrated method is shown in Fig. 6. First, the main environmental variables with their lower and upper bounds need to be selected based on the design considerations (Step 1). Initial samples of the chosen environmental variables,  $X$ , over the entire design space is required (Step 2). The initial samples provides the input for the numerical simulations, which predict the misalignment angle,  $Y$  using the iterative routine (Step 3). A metamodel,  $\hat{F}(X)$ , is then established for the misalignment angle based on  $X$  and  $Y$ . The metamodel constructs the relationship between the design variables and corresponding responses to replace the



**FIGURE 6:** Flowchart for the integrated method using metamodels.

original complex numerical models (Step 4). Finally, for a given site with available environmental conditions, the misalignment angle for this specific site can be predicted efficiently using the metamodel,  $\hat{F}(X)$  (Step 5). The methodology and discussions on the main steps involved in the integrated method is detailed as follows.

### Sampling of environmental variables

The responses of the fish farm structures depend on the site condition, which normally includes wind, waves and currents. In this study, we focus on the waves and currents, and the variables include significant wave height ( $H_s$ ), wave spectral peak period,  $T_p$ , mean current velocity,  $U_c$ , and the directional difference between the waves and current,  $\Delta\theta$ . Because the single-point mooring system makes the whole structure weathervane, the direction difference  $\Delta\theta$  will determine the equilibrium heading for the structure instead of the individual wave and current directions. The variables and the corresponding lower and upper bounds are listed in Table 2.

**TABLE 2:** Design variables and their lower and upper bounds

Variables	Lower and upper bounds
$H_s$	0 - 8 (m)
$T_p$	2 - 20 (s)
$U_c$	0 - 1.5 (m/s)
$\Delta\theta$	0 - 180 (deg)

An initial sampling of variables over the entire design space is required, and it is a problem in the design of experiments (DOE) [23]. This problem has been studied extensively on the design and analysis of computer experiments. The commonly used DOE includes uniform design, random sampling, Latin hypercube sampling and orthogonal arrays [20]. In the case study, we employ the Latin hypercube sampling (LHS) method. LHS is a strategy for generating random sample points ensuring that all portions of the vector space is represented [24]. The LHS strategy divides the interval of each dimension into non-overlapping intervals having equal probability. Random samples in each interval of each dimension are generated and the points from each dimension are paired randomly.

In the present study, LHS method is applied for the sampling of the five environmental variables in Table 2, and 6000 pairs of samples are used as input for the numerical simulations for Step 3 in the integrated method (Fig. 6).

### Application of metamodels

In the integrated method, metamodels are constructed between the environmental variables and the simulated misalignment angles. With a metamodel, the misalignment angle distribution for a given site with a large database of metocean data can be predicted efficiently. There are different types of metamodels, such as Kriging models [25], neural networks [26], radial basis functions [27] and polynomial functions [28]. Detailed metamodeling strategies can refer to the above cited literature. In the current study, the Kriging model is applied.

The Kriging model estimates the value of the output from the sum of the weighted values of the known surrounding sample points,  $X = (x_1, \dots, x_n)$ . The corresponding responses,  $Y = (y_1, \dots, y_n)$ , of these sample points  $x_i$  are obtained from the complex numerical model simulations. Then, a predicted value  $\hat{F}(x)$  is expressed in two parts as:

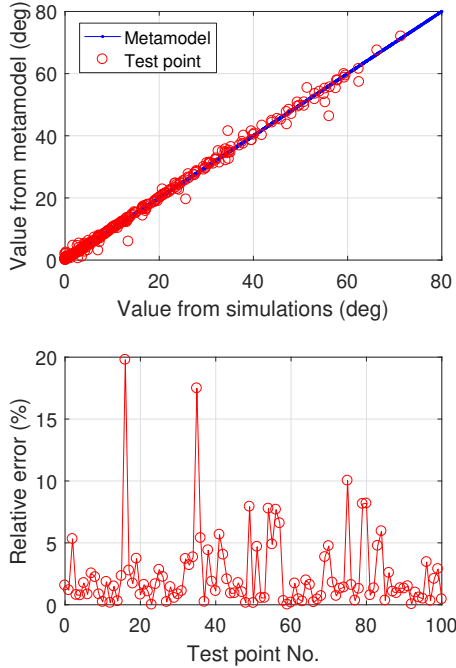
$$\hat{F}(x) = f(x) + \delta(x) \quad (8)$$

where  $f(x)$  is the regression function, and  $\delta(x)$  is a random function (stochastic process) to describe the residuals. The regression functions capture the data, and the stochastic process interpolates the residuals. The regression function is a linear combination of the chosen functions, such as multivariate polynomial functions. The random process,  $\delta(x)$ , is assumed to have zero mean and covariance between  $\delta(x_i)$  and  $\delta(x_j)$ :

$$Cov[\delta(x_i), \delta(x_j)] = \sigma^2 R(\theta, x_i, x_j) \quad (9)$$

where  $\sigma^2$  is the process variance and  $R(\theta, x_i, x_j)$  is the correlation model with parameter  $\theta$ . The two common types of the correlation model are the Gaussian and exponential correlation functions. By minimizing the errors between the predictor and the data points, the parameters involved in the correlation function can be obtained.

Validation of metamodels is important before being used as



**FIGURE 7:** Validation of the Kriging metamodel using additional simulation points.

a ‘surrogate’ of the numerical models. Both cross-validation using available data points or validation by employing new test points can be used. Fig. 7 presents the validation of the Kriging model for the calculated misalignment angle. 150 new points in addition to the initial samples are used for the validation. Reasonable agreements between the predicted values from Kriging model and the actual simulation results are reached. The relative errors between the two values are also presented for the test points with misalignment angle larger than 10 degrees to avoid the large errors when the values are close to 0. The relative error is defined in Eq. (10).

$$R = \left| \frac{y_i - \tilde{y}_i}{y_i} \right| \times 100\% \quad (10)$$

where  $\tilde{y}_i$  is the predicted value using Kriging model and  $y_i$  is the actual value from numerical simulations. It is seen that except two test points, most of the relative errors are below 10%. The validation shows the acceptable accuracy of the Kriging model, and thus using this metamodel to replace the numerical simulation code is feasible. To increase the accuracy of the metamodel, more samples for simulations may be required. Furthermore, different metamodels can be employed and compared to select the most suitable model.

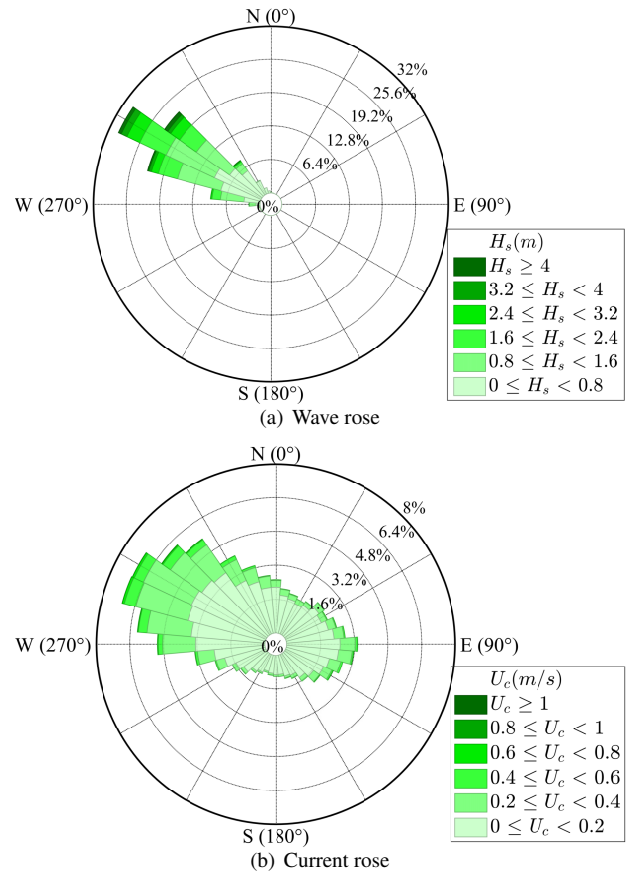
### PREDICTION OF THE MISALIGNMENT ANGLE FOR A REFERENCE SITE

A case study is presented in this section using the proposed integrated method. The established metamodel is applied to

predict the misalignment angle between the vessel and the currents for a typical exposed site for fish farms. A short description of the site condition is presented first, followed by results and discussions.

### Wave and current conditions at the reference site

A reference site, Breisundet, in the west coast of Norway is selected for the case study. The coordinate of the site is 62.43901°N 5.92953°E, located close to the city Ålesund. The water depth is 345 m. The wave and current conditions were measured using wave buoys and acoustic Doppler current profiler. The wave and current data for every 10 min over the period from October 2016 to November 2017 are used in the analysis. Wave spectral parameters  $H_s$  and  $T_p$  were extracted from the measurements. The current velocity was measured over the depth from the free surface to 100 m below, and the velocity at 30 m below the free surface is used for the calculation of current forces on the whole fish farm structure.



**FIGURE 8:** Wave and current roses for the reference site.

The maximum  $H_s$  is found to be 6.9 m and the maximum

current velocity  $U_c$  is 1.4 m/s. Based on the classification of the wave and current conditions in the Norsk Standard NS 9415, the maximum current condition for this site is considered as ‘high exposure’ ( $1\text{ m/s} < U_c < 1.5\text{ m/s}$ ), while the extreme wave condition belongs to the highest wave class ‘extreme exposure’ ( $H_s > 3\text{ m}$ ).

Figure 8 presents the wave and the current roses for the reference site based on the one-year data. The directions are defined as the coming direction of the waves or currents. Most of the waves come from the north-west with little directional scatter. The general circulation in the local area includes tides with a period of around 12 hours and wind-driven currents. The main direction of the wind-driven currents are aligned with the main wave direction, but with more spreading compared to the waves. The tides also contribute to the currents from the east and south-east. In general, for the reference site, large waves and currents are mostly aligned or with small direction differences. Misalignment conditions with direction differences larger than 30 degrees often appear when the current velocities are less than 0.6 m/s.

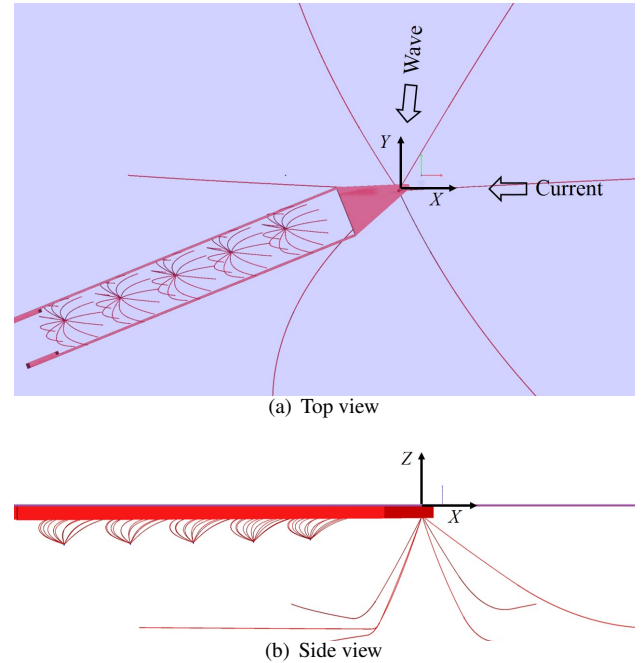
In the static analysis, unidirectional irregular waves are modeled using the JONSWAP spectrum. Uniform current profile is assumed for the calculation of loads on the net panels.

### Results and discussions

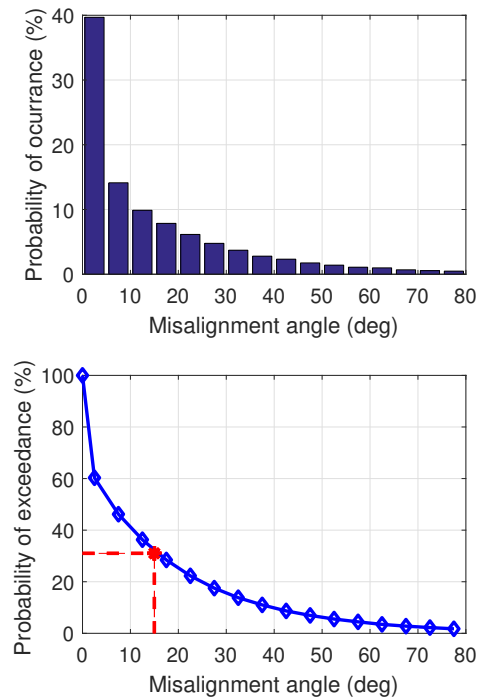
Figure 9 shows the top and side views of the static equilibrium of the fish farm structure under a typical misaligned wave and current condition in SIMA program. It is obvious that the deformation of the flexible cages is significant under the current velocity of 1.28 m/s. The individual cage deformation weakens from cage 1 to cage 5 because of the current velocity reduction. For the same reason, deformations of the upstream net panels are observed to be larger than those of the downstream net panels within one cage. The misalignment angle between the vessel heading and the current is 22.2 degrees for the illustrated case.

By using the one-year combined wave and current conditions and the established metamodel, the misalignment angle between the vessel and the currents are predicted for the reference site. Fig. 10 presents the probability distribution of occurrence and probability of exceedance for the misalignment angle over the studied period. It is seen that the vessel and the current are almost aligned for 40% of the situations with misalignment angle less than 5 degrees. The total probability of occurrence with the misalignment angle over 20 degrees is around 20% for this site.

As mentioned previously, DP system may be required to rotate the vessel and increase the misalignment angle for a better flow condition in the cages. From a practical point of view, a threshold value for the misalignment angle need to be determined to activate the DP system. This threshold value for the misalignment angle should ensure a sound living environment for



**FIGURE 9:** Equilibrium condition of the fish farm structure under uniform currents ( $U_c=1.28\text{ m/s}$ ,  $Dir_c = 180\text{ deg}$ ) and waves ( $H_s = 6.29\text{ m}$ ,  $T_p = 10.21\text{ s}$ ,  $Dir_w = 261\text{ deg}$ ).



**FIGURE 10:** Probability of occurrence and exceedance for the misalignment angle during one year.



the fishes in all cages, and it should be determined by assessing the flow conditions in the cages. However, to quantify the flow conditions inside each cage is a challenging task. The flow is affected by many factors, including the current reduction between the cages, the solidity ratio of the nets, the vessel motions, the deformation of the cages, and fish movements. Among these factors, it is obvious that current reduction between the cages depends greatly on the misalignment angle between the structure and currents, while other factors are little affected. Thus, it is considered reasonable to use current reduction factor to represent the flow conditions for changing misalignment angle.

Several experimental studies on the current reduction in the fish cages can be found in the literature [11, 29]. These studies observed up to 20% of flow reduction after a single net panel with various solidity ratios. A few field measurements have reported more than 30% of current reduction in a single cage with solidity ratio around 0.15 [30]. To provide a better overview between the misalignment angle and the usage of DP system, a reference value for the current reduction factor is assumed as  $R = 0.2$ . This implies that the flow condition is considered acceptable when the current reduction factor is lower than the reference value, i.e.,  $R < 0.2$  for all five cages.

Table 3 presents the averaged reduction factor for a solidity ratio of 0.2, which is the mean value of the reduction factors from the net panels located in the upstream of the cage. The calculations are based on Eqs. (5) to (7) and the method shown in Fig. 5, and the estimation is based on non-deformed net panels.

**TABLE 3:** Averaged current reduction factors,  $R$ , inside each cage under different misalignment angle  $\alpha$  ( $S_n = 0.2$ ).

$\alpha$	Cage 1	Cage 2	Cage 3	Cage 4	Cage 5
0°	0.106	0.286	0.429	0.544	0.635
5°	0.106	0.225	0.303	0.345	0.365
10°	0.106	0.201	0.240	0.225	0.225
15°	0.106	0.181	0.186	0.186	0.186
20°	0.106	0.176	0.176	0.176	0.176
25°	0.106	0.149	0.149	0.149	0.149
30°	0.106	0.144	0.144	0.144	0.144

It can be observed from Table 3 that the current reduction factor increases dramatically from Cage 1 to Cage 5 when the misalignment angle ( $\alpha$ ) is below 10 degrees. This is due to the wake shielding effects as the net panels in the following cages are positioned behind the upstream panels. The average reduction factor in Cage 5 is over 60% when the vessel is aligned with the currents. This means when the incoming current is 1 m/s, the averaged current velocity inside Cage 5 is lower than 0.4 m/s. The high reduction factor indicates lower levels of

dissolved oxygen and increased wastes from the upstream cages. Both factors may significantly affect the fish health [31]. With a misalignment angle larger than 15 degrees, the current reduction factors reach similar values for Cage 2 to Cage 5. In this case, the current comes from one side of the vessel, and many net panels in Cages 2 to 5 are exposed to the current and not sheltered by other net panels. Thus, the current reduction factor is lower.

Based on the estimated reduction factors in Table 3, the requirement for reduction factor lower than the reference value,  $R = 0.2$ , is equivalent to the misalignment angle  $\alpha > 15^\circ$ . Therefore, if the misalignment angle is less than this threshold value  $\alpha = 15^\circ$ , thrusters and DP systems will function to rotate the vessel to improve the flow condition. Referring to the probability distribution of the misalignment angle for the reference site in Fig. 10, it can be found the probability of requiring DP system is around 70% based on the assumed threshold value. Thus, for most of the time the thrusters need to be at working condition to improve the flow condition, in particular for Cages 4 and 5. However, the estimation of the power requirement for the DP system needs more detailed studies on the mean loads on the whole structure from currents and waves when  $\alpha < 15^\circ$ . These studies will be carried out in the future work.

It should be aware that, the solidity ratio of the nets influence the drag coefficients on the fish nets significantly. When a higher solidity ratio applies, the drag forces on the nets will increase, resulting in lower misalignment angles between the vessel and the currents. Moreover, the current reduction on the downstream cages will also increase compared to the results shown in Table 3. Both effects will lead to a significant rise of the demand for the DP system. Detailed studies with increased solidity ratio due to biofouling on the misalignment angle will be investigated in our future studies.

## CONCLUSIONS AND FUTURE WORK

This paper presents a numerical study to predict the misalignment angle between the heading of the vessel-shaped offshore fish farm and the incoming currents. The misalignment angle can be useful for the design of the dynamic positioning system for the fish farm. An integrated method using metamodels is proposed. The metamodels are used as surrogates for the complex numerical simulations. The probability distribution of the misalignment angle for a reference site in Norway has been predicted. It was shown that the vessel and the currents are aligned for 40% of the time during the one-year period for the reference site using solidity ratio of 0.2 for the nets. By estimating the averaged current reduction factors inside each cage under various misalignment angles, a reasonable threshold for the misalignment angle is found to be 15 degrees for the chosen solidity ratio. Based on the angle distribution and the threshold misalignment angle, it is found the probability of requiring DP system is around 70% of the

time for the reference site. The metamodel used in this work proves to be efficient for estimation of the responses under a large number of environmental conditions, and it can be used for similar applications.

In this study, the misalignment angle is based on static calculations where the whole coupled system reach a equilibrium under mean wave drift forces on the vessel and mean current forces on the mooring lines and the fish nets. However, in real situations, the whole system experiences dynamic motions under irregular waves and currents. The mean position in dynamic conditions may deviate from the one calculated from static conditions due to additional mean forces from the waves on the fish nets. Moreover, the wind forces on the super structures may also influence the misalignment angle. These aspects need to be studied in the future work.

Furthermore, the flow conditions inside the fish cages are important for the fish health, and quantitative methods to predict the flow conditions are essential. It is recommended to study the flow conditions inside the fish cages using more advanced numerical (e.g., computational fluid dynamics) or experimental methods considering the deformation of the nets and the interactions between the cages. The quantitative analysis of the flow condition can provide a better criteria for the misalignment angle and can improve the design of the DP system.

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