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Hydrodynamic response of a cage system under waves and currents using a Morison-force model

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ABSTRACT

Accurate computation of forces and deformations on cages under wave and current loads is a key element when designing mooring systems for fish farms. In this study, an analysis of a cage under combinations of current and wave loading is carried out and the numerical results are compared with experimental data. The numerical tool used in this analysis is based on a Morison-force model. For the case of single frequency tests, drag and inertia coefficients for the surface collar are selected based on *Re* and *KC* numbers. For irregular wave conditions, coefficients in Morison equation are selected based on significant wave height and peak period. Net is represented by an equivalent array of cylinders, which considers the same wet mass, projected area, and axial stiffness as the prototype net. This approach allows discretizing the net using a small number of elements. The present model predicts the loads over the floating collar as well as the drag force over the net. Overall, the study shows that current load dominates for most of wave and current conditions analyzed; yet, for large and steep waves, its effect is of similar importance as the current load.

1. Introduction

Capture fishery stocks have been exploited during the last decades, due to the rapid growth in human population. In response to this rise in demand, aquaculture production has increased up to 40% of the total seafood consumed in the world (FAO, 2016). This translates into a growth in volume of fish cages, in addition to an upsurge in the biomass density (Jensen et al., 2010). Nowadays, the industry is considering moving production centers further offshore where water quality and space availability favor production intensification. In offshore locations, a fish farm must be able to operate under minimal human intervention, in higher sea states with stronger moorings (Cifuentes and Kim, 2015a; DeCew et al., 2005; Drach et al., 2013; Shainee et al., 2012). For cages installed in offshore sites, numerical tools are essential to safeguard the integrity of fish farm structures and mooring systems.

Numerical methods to determine the hydrodynamic response of a cage must be capable to deal with a moving boundary as the net deforms with current and waves going through the cage. A model must consider the different scales of the elements on the cage. It is not practical; however, to model every element of the net due to the small diameter, therefore an equivalent net must be created. The surface and bottom collar can be model using the same dimensions and properties as in the physical system. Even though the net represents the main component of a cage, a reliable modeling of the surface collar needs to be incorporated, given that the load over the floater has a great influence on the total load and motions of the cage under wave conditions (Kristiansen and Faltinsen, 2015). Several studies have been carried out to predict loads over cages including structural, hydrodynamic, and biological effects that might influence the response of the structure to a variety of load conditions. A review of these studies can be found in Klebert et al. (2013).

Some numerical tools are based on Morison equation using a line element model (Bi et al., 2014; Cifuentes and Kim, 2015b; Moe-Føre et al., 2015), Morison equation models have also been developed using a consistent net element (Tsukrov et al., 2003) and screen force model (Kristiansen and Faltinsen, 2012; Lader and Fredheim, 2006). These methods have been validated with experiments, including current and wave loadings. In many of these experimental studies, a stiff surface collar has been used considering constant values for inertia and drag coefficients (Huang et al., 2010; Lader and Enerhaug, 2005; Xu et al., 2011; Zhao et al., 2007b). Most of the studies including current and irregular waves have been done using the consistent net element approach (DeCew et al., 2005; Fredriksson et al., 2007, 2005, 2003b). In the present analysis, a methodology to obtain the hydrodynamic response of a cage under irregular waves and current, and the

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corresponding selection of drag and inertia coefficient for floater and net using the existing numerical method is presented.

In long wave conditions, a cage will follow the wave elevation and a linear relation can be observed between wave elevation, surge and heave motions (Dong et al., 2010). For high wave frequencies, f > 1.0 Hz, negligible motion is observed, evidence of the high damping present in the system (Xu et al., 2011), which was also observed in a SPAR cage where the natural period in heave reached 22 s (Fredriksson et al., 2003a).

Under wave loading, the dynamic response of the floating collar including flexible modes can significantly influence on the global response of the cage (Endresen, 2011; Faltinsen et al., 2011). For the whole cage system under waves only condition, mooring line dynamic forces are strongly dependent on wave elevation and negligible volume reduction is observed, which is driven by current loading. Large deformations are expected with the surface collar due to low bending stiffness (Li et al., 2013a). In addition, the wave kinematic approximation to the instantaneous free surface is important to consider since the floating collar load can be significant (Kristiansen and Faltinsen, 2015).

In the present work, a single cage consisting of a flexible surface collar, netting, ballast, and mooring system is exposed to a combination of current and regular/irregular waves. The cage is assumed to be empty inside and open at the top and bottom following the same experimental and numerical conditions described in Kristiansen and Faltinsen (2015), to validate the calculations used in this study. The numerical model is built using a commercial software. Previous studies by the authors showed the accuracy of load calculations especially for the current-only condition when shielding effect is included (Cifuentes and Kim, 2015b). Particular attention is given to the drag and inertia coefficient selection for the upper collar, which depends on the wave condition characterized by Keulegan-Carpenter *(KC)* and Reynolds *(Re)* numbers. The definition of drag coefficient for the net is based on a semi-empirical formulation which accounts for the blockage of the flow at high current speed. This formulation has been obtained particularly for Raschel nets and it covers a wide range of solidity ratios (S_n) and Reynolds numbers (Cifuentes, 2016). An analysis of the effect of different models for wave kinematics extrapolation above the mean water level over the response of the cage was also performed.

The last part of the present study investigates the cage in irregular waves and a combination of irregular waves and steady current. The mooring line tension results are provided in the time and frequency domain to evaluate the relative importance of wave and current loading over the system.

2. Numerical model

2.1. Equivalent net model

The numerical model is built using a commercial software. This software is able to account for nonlinearities such as viscous drag loads as well as large displacements of elements (Orcina, 2014). The complete cage system, composed of a floating collar, netting and ballast, is modeled by a combination of line elements, three and six degree of freedom buoys. Line elements represent netting and surface collar. The structural model of a line is a massless spring with a node at each end where mass, buoyancy, inertia and drag forces are lumped (Orcina, 2014). The lines representing the netting are connected using three degree of freedom buoys, which transfer only translational motions since bending stiffness of the net is negligible in the present case.

For the surface collar, lines are connected by six degree of freedom buoys, which transfer rotational and translational motion to represent the bending stiffness of the material. This property is critical on the response of the cage under regular and irregular wave loading. In a cage, ballast can be either distributed over a bottom rim or applied as hanging weights at certain points along the circumference of the net. Both systems can be represented in the numerical tool used in this analysis. For this particular case, point masses are used and represented by an increase on the mass of particular buoys at the bottom corresponding to the locations of the concentrated ballast points on the experimental model used as validation. The buoys connecting these line elements, however, do not add any inertial or drag loading on the system.

Since a typical net has a large number of threads, its exact numerical representation is unfeasible, thus an equivalent net must be created. This array of line elements must be able to represent the motions and deformation of the physical system (Tsukrov et al., 2003). This is achieved by matching wet mass, projected area and axial stiffness between the physical and numerical models of the net pen. The solidity ratio (S_n) is defined as the ratio between the projected and total area of a net panel, and is used to match the viscous drag load. Wet mass similarity is achieved by adjusting the buoyancy of the connecting buoys. Since the buoyancy and mass of line and buoy elements are lumped into the nodes, the total wet mass of the equivalent net corresponds to the wet mass in the physical net. Axial stiffness of the net is done by modifying Young's Modulus with the technique described in Fredheim (2005). In this manner, a small number of elements are required to achieve a relative error of less than 10% between numerical results and experimental data (Cifuentes and Kim, 2015b). Fig. 1 shows the procedure to go from the physical net to an equivalent numerical net including line and buoy elements, and finally the complete cage.

2.2. Morison force model

The main force component over the netting on a cage comes from the viscous drag load. This is based on the analysis of the dimensionless Keulegan Carpenter (*KC*) number, which represents the ratio between drag and inertia loading for cylinders in oscillatory flow (Keulegan and Carpenter, 1958). Due to the small twine diameter of the net (0.6 mm), values for *KC* numbers, for the wave conditions analyzed, ranged between 50 and 2000 where drag is dominant. At this range, the vortex shedding frequency is larger than wave frequency and flow conditions resemble a steady flow (Faltinsen, 1993; Journée and Massie, 2001). Under these flow characteristics, inertia loading can be neglected.

Hydrodynamic forces over the cage are calculated based on a modified version of Morison equation, considering relative motion between line element and fluid flow (Haritos and He, 1992). The cross flow principle is applied to account for the angle of attack's effect over hydrodynamic force (Hoerner, 1965). The formulation is presented in Eq. (1).

$$F_W(t) = \frac{1}{2}\rho C_d dl\,[v(t) - u(t)]|v(t) - u(t)| + \rho C_M \frac{\pi}{4} d^2 l \dot{v}(t) - \rho (C_M - 1)\frac{\pi}{4} d^2 l \dot{u}(t) \quad (1)$$

In Eq. (1), $F_w(t)$ is the fluid force, ρ is water density, d is element effective diameter, l is length, C_M and C_d are inertia and drag coefficients, $u(t)$ and $v(t)$ are element and fluid velocities while $\dot{u}(t)$

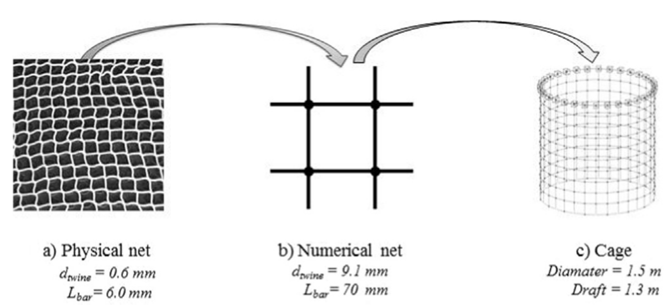

Fig. 1. Equivalent numerical model of the cage.