Modelling of Net Structures Exposed to 3D Waves and Current

Pål F. Lader¹ and Arne Fredheim²

Abstract

A numerical model of a 3D net cage exposed to waves and current are being developed at SINTEF Fisheries and Aquaculture. As a first part of this work a numerical model of a simple net exposed to 3D waves and current has been developed. In this model the net is divided into plane flexible net elements, and structural and hydrodynamic forces are calculated for each element. The movement of the net is found from time integrating the equation of motion in each node.

The model is used to study the influence of different parameters on the behaviour of the net. Through six different cases the impact of the following six parameters are investigated: i) Net orientation relative to waves and current, ii) floater movement, iii) wave period/height, iv) current velocity, v) net solidity and vi) bottom weight.

Introduction

The fish farming and aquaculture industry are expanding, and the demand for

¹. Research Scientist, SINTEF Fisheries and Aquaculture, N-7465 Trondheim, Norway, Phone: +47 73 59 76 92, fax: +47 73 59 56 60, e-mail: Pal.Lader@fish.sintef.no
². Research Scientist, SINTEF Fisheries and Aquaculture, N-7465 Trondheim, Norway. Phone: +47 73 59 56 50, fax: +47 73 59 56 60. E-mail: Arne.Fredheim@fish.sintef.no
suitable locations for fish farms is increasing. In Norway, as well as in other countries, this calls for new technological challenges, as fish farms are being installed at locations more exposed to waves, wind and current. In the future it is clear that more of the fish farms have to be located offshore, as the number of suitable near-shore locations are limited. A move towards the use of offshore locations are also motivated by environmental and aesthetic aspects of the industry, and future fish-farms will most likely be in the form of large scale offshore installations, rather than small near-shore farms. Before the installation of such structures it is, however, necessary to assess the behaviour of the structure when it is exposed to the environmental forces typical for the location. In contrast to the present day offshore oil installations, which are rigid body structures, the fish farms are complex flexible structures with an infinite number degrees of freedom. This makes it necessary to develop new numerical tools for simulating the behaviour of such structure.

As a first step towards a full 3D dynamic model of a fish cage, a model of a single net panel is developed. The single net panel model is going to form the basis for the full 3D model, and will be described in this paper, together with preliminary results and verifications.

Model description

Overview

The net is divided into panel elements (Fig. 1). Each panel is assumed to be plane, but is otherwise allowed full flexibility. Hydrodynamic and structural forces are calculated for each element based on the wave particle velocity, current velocity...
and structural velocity. The floater movement are not modelled at present, and the top point can either be fixed or be forced to follow the wave surface in heave with a fixed horizontal position. The bottom point has a weight attached (this weight is not modelled, and mass and weight is simply added to bottom point). The forces on each element are then distributed equally to its two node points. The mass is also distributed to the node points, and the equation of motion \( F = ma \) is then evaluated in each node, yielding the acceleration. The position as well as the velocity of the nodes are then found from time integrating the acceleration.

**Plane element criterion**

Movement of the node points are not restricted, and the node points are allowed full 3D movement. The elements are though restricted to be plane, and this is accomplished by defining a orientation vector \( \mathbf{n}_o \) which is the vector parallel to the straight line dividing two elements (Fig. 2). For the elements to remain plane while the node points are allowed full 3D movement, the criterion is that the orientation vector must be constant in time, and equal for all elements.

**Hydrodynamical forces**

The hydrodynamical forces for each element are divided into drag \( \mathbf{F}_D \) and lift \( \mathbf{F}_L \) force. The drag force being parallel to the flow direction \( \mathbf{F}_D \parallel \mathbf{U} \), while the lift force is perpendicular to the flow direction \( \mathbf{F}_L \perp \mathbf{U} \). The forces one each net element are calculated from:

\[
\mathbf{F}_D = \frac{1}{2}\rho C_D A |\mathbf{U}|^2 \mathbf{n}_D
\]  

---

1. Bold type faces indicates vectors
\[ F_L = \frac{1}{2} \rho C_L A |U|^2 n_L \]  

where \( \rho \) is the water density, \( C_D \) and \( C_L \) are the drag and lift coefficients respectively, \( A \) is the element area, \( U \) is the relative velocity between the fluid and the net element, while \( n_D \) and \( n_L \) are the unit vectors in the direction of the drag and lift force respectively.

The drag and lift coefficients were calculated using formulas found by Aarsnes et al. (1990) based on both theoretical work and comprehensive model tests:

\[
C_D = 0.04 + (-0.04 + S - 1.24S^2 + 13.7S^3) \cos(\alpha) \quad (3)
\]

\[
C_L = (0.57S - 3.54S^2 + 10.1S^3) \sin(2\alpha) \quad (4)
\]

Here \( S \) is the solidity of the net, which is the ratio between the projected area of the net \( (A_p) \) and the total area enclosed by the net \( (A) \): \( S = A_p/A \). \( \alpha \) is the angle of attack, and is defined to be the angle between the direction of \( U \) and the normal vector of the element (Fig. 2). The above formulas (Eq. 3 and 4) should not be used for \( S \) higher than 0.35. Aarsnes et al. (1990) compared the formulas with experimental work done by other investigators, and found good agreement. The element area \( A \) is not constant, but varies with the deformation of the element. Consequently the solidity \( S \) also varies accordingly since the projected area of the net element \( (A_p) \) is constant. The solidity used to calculate the hydrodynamical forces on each net elements must therefore be corrected for on each individual element based on the instantaneous area of that element:

\[
S = S_0 \frac{A_0}{A} \quad (5)
\]

where \( S \) and \( A \) is the instantaneous solidity and area of the element respec-
tively, and $S_0$ and $A_0$ is the solidity and area of the net when it is undeformed.

It is assumed that $U$ is constant over the whole area of the element, and the velocity is evaluated in the element centre:

$$U = U_w + U_c - U_s$$

(6)

where $U_w$ is the wave particle velocity, $U_c$ is the current velocity and $U_s$ is the structural velocity (the velocity of the element). A Stokes 5th order wave model is used to calculate the wave particle velocities and the wave surface elevation. The details of the model can be found in Fenton (1985). No interaction between the waves and the current is at this point incorporated in the model.

The unit vectors for drag and lift are found from:

$$n_D = \frac{U}{|U|}$$

(7)

$$n_L = \frac{(U \times n_{en}) \times U}{|(U \times n_{en}) \times U|}$$

(8)

where $n_{en}$ is the unit normal vector of the net element. The direction of $n_{en}$ is in the positive flow direction.

**Structural forces**

The net element is assumed to have structural characteristics similar to that of a non linear spring. Tronstad (2000) has done experiments on the behaviour of net panels exposed to tension, and some of the results are presented in Figure 3. Based on these results, the relationship between force and elongation is assumed to be described by:

$$F_s = A\varepsilon^2 + B\varepsilon \quad \varepsilon > 0$$

$$F_s = 0 \quad \varepsilon \leq 0$$

(9)
where $F_s$ [N] is the structural force, and $\varepsilon$ [-] is the global elongation. The global elongation is given by $\varepsilon = (l - l_0)/l_0$ where $l_0$ is the un-deformed length and $l$ is the deformed length of the panel. $A$ and $B$ are constants.

Equation of motion

The hydrodynamic and structural forces acting on each element are equally distributed to each node (Figure 4). The equations of motion ($F = ma$) are then evaluated in each node:

$$-F_s^{n-1}n_e^{n-1} + F_s^{n}n_e^{n} + \frac{1}{2}(F_d^{n-1} + F_d^{n} + F_f^{n-1} + F_f^{n}) + \frac{1}{2}(w_{n-1} + w_{n})g n_g = \frac{1}{2}(m_{n-1} + m_{n})a_n$$

Time integration

From the equation of motion the acceleration of each element is found. To calculate the movement of the node, the acceleration is integrated twice:

$$u = \int adt$$

$$x = \int u dt = \int \int adt dt$$

The integration is done using a Rung-Kutta method of order 4. A description of this method can be found in several textbooks, e.g. Cheney and Kincaid (1985).

Test cases and verification

The model was verified by comparing it to another numerical model: The computer program NETSIM (Løland and Slaattelid, 1993 and Rudi et al., 1998), which is a quasi-static model. The NETSIM computer program has again been validated against results from model tests. The dynamic model presented in this paper was found to give reasonable agreement with the quasi-static model in NETSIM (Lader et al., 2001). Further verifications against laboratory or full scale measure-
ments are however necessary to fully assess the validity of the dynamic model.

**Simulation cases**

A single net, 2 m wide, and 10 m deep, divided into twenty equally sized elements is used in the simulation cases (Fig. 5). The net is assumed to have flag oriented mesh, and the elasticity in the net is taken to be equal to the net in Figure 3. A least square fitt gave \( A = 37 \, 335 \, [N] \) and \( B = 1 \, 162 \, [N] \) (see Eq. 9) for a net panel of 1 [m] width. It is assumed that the force is linearly dependent on the width of the element.

The Six parameters (net orientation, top point movement, wave, current, net solidity and bottom weight) are chosen, and the influence of each of these parameters on the behaviour of the net is observed through six case studies. Table 1 shows the parameters and parameter settings used in the different cases. In each case one of the parameters are varied, while the other parameters are kept constant.
Discussion

Case 1. Net orientation. This case illustrates the three-dimensionality of the model; how the model works when the net is exposed to waves/current at an angle (other than perpendicular at). The waves and current are propagating in positive x-direction, and the net is oriented with different angles relative to the wave/current direction. The results from the simulations are shown in Fig. 6, where the trajectories of three of the nodes (node nr. 3, 10 and 21, counting from the top) are shown in the xy-, and the xz-plane. When the net is oriented parallel or normal to (0° or 90°) the movement of the net is confined to the xz-plane. Both the velocity vector \( \mathbf{U} \) and the...
element normal vector \( \mathbf{n}_{en} \) lies in the zx-plane, and thus all forces on the elements lies in this plane and no forces have components in the y-direction. However, when the net has an orientation relative to the wave/current direction other than \( 0^\circ \) or \( 90^\circ \), the net also moves in the y-direction. For this cases \( \mathbf{n}_{en} \) is not bound to the xz-plane, and thus forces on the elements have components in the y-direction.

**Case 2. Top point movement.** This case illustrates clearly the influence of the floater movement on the structural forces in the net. Figure 7 shows the time history of the element structural force in the top and bottom element when the net is exposed to waves (the wave elevation are shown in the top plot). The element structural force in these two elements represent the structural forces in the joint between the net and the floater, and between the net and the bottom weight. When considering fish cages a fault in the net/floater joint will most likely allow large quantities of fish to escape, with negative consequences both economically and environmentally. If the joint between the bottom weight and the net fails, this can cause a collapse of the net volume, which again will impoverish the fish environment and result in higher fish mortality. Thus these two properties (top and bottom element force) are important when designing a fish cage, and they will be used extensively in this analysis.

When comparing the forces in the net when the top point is fixed with the forces when the top point is forced to move with the wave, the importance of the floater movement is obvious. For the net where the top point follows the wave relative to the net with fixed top point, the dynamic amplitude of the force is approximately 5 times larger in the floater/net joint, and 10 times larger in the net/bottom weight point. The floater movement is therefore the main contributor to the forces and tensions in
the net, while the forces which are only connected with the fluid/structure interaction on the net are much smaller. This implies the importance of modelling the behaviour of the floater accurately in order to obtain good estimates for the structural forces in the net.

For the net with the moving top point it can be observed that the force in the top element goes to zero (arrow 1) when the force is on its minimum. The net acts as a one directional spring (see Eq. 9), and this causes a slack in the net when the movement of the floater is too large. The large dynamic amplitude of the force in the bottom element is a direct consequence of this slack; the spikes in the curve representing the minimum and maximum force (arrow 2 and 3 respectively) in the bottom element coincides with the beginning and ending of the period when the top element force is zero. Situations where the net experiences a slack should be avoided, since this causes large forces which can result in net fault.

Case 3. Wave. The net is exposed to waves with different wave periods (the steepness\(^1\) of the wave is the same for all the three waves), and the forces in the top and bottom element are examined. As could be expected; the wave with the longest period (T=4s) and height (H=1.78) produces the largest forces in the net. Again it can be observed that the force in the top element goes to zero (arrow 1), and there is a slack in the net which results in spikes in the bottom element force (arrow 2).

Higher harmonic components with considerable amplitude are present in the bottom element force time history. Figure 9 show the spectral density of the element (top and bottom) force time history for T=4s (dashed line in Fig. 8). For the top ele-

---

1. Steepness is the wave height divided by the wave length.
ment, the first harmonic component with frequency equal to the wave period (frequency $f = 0.25$ Hz) is dominating. For the bottom element, however, this has changed and now the harmonic component with frequency $3f$ is dominating. This change in dominating frequency influences the possibilities of fatigue induced faults to occur, and must be taken into account when the bottom weight joint are designed.

**Case 4. Current.** Three different levels of current in combination of waves ($T=3s$, $H=1m$) are applied on the net, and the force in the top and bottom element together with the drag force are presented in Fig. 10. The drag force is the horizontal component of the element structural force in the top element, and it is this force that is acting on the mooring system of the installation. It is therefore important to consider this force in addition to the net forces when the whole layout of the installation is designed.

The dynamic amplitude of the forces in the top element is approximately equal at the start of the simulation. At the end however, the dynamic amplitude of the no current case is considerably larger then that of the current cases. This is due to the mean net deformation because of the current. With no current the mean position of the net is approximately straight down, while the mean position of a net exposed to waves and current is approximately equal to the static deformation of the net when it is exposed to current only (see Fig. 11). This deformation due to the current influences the forces from the waves in such a way that they decreases.

When considering the bottom element load it is apparent that the net not exposed to current experiences the largest loads. The spikes in the bottom element force for the no current case is due, as before, to the slack in the net. This can be
observed from the top element force which goes to zero at its minimum. The current prevents the net from going into slack, and thus the bottom element does not experience as large fluctuations as for the no current case. In general current will reduce the probability of slack occurrence.

The drag force is larger for the current cases than for the no current case. This is purely due to a change in the angle between the top element and the horizontal plane because of the current. As illustrated in Fig. 11, the current causes the angle between the top element and the horizontal plan to be smaller, and consequently the drag force (horizontal component of the top element force) becomes larger (assuming constant element force). Thus the presence of current results in higher drag forces and higher loads on the mooring.

The drag force on a net exposed to waves and current i opposing directions has considerable higher harmonic components. This can, as noted earlier, have an effect on the probability of fatigue failure and should be taken into account when moorings are designed.

**Case 5. Net solidity.** Anything that over a long period of time is submerged in sea tends to get overgrown with different kinds of marine organisms. This growth can change the behaviour of the net, and must be considered when the installation is supposed to be in the sea for a considerate period of time. As a simple approximation, the growth can be modelled as an increase in the net solidity, and by comparing nets with different solidity the effect of marine growth can be estimated. Figure 12 shows the element structural force for nets with different solidity exposed to waves and current. The dynamic amplitude of the top element force is approximately equal for the nets
with solidity 0.05 and 0.10 (slightly larger for solidity 0.10 in the first few periods). For the net with solidity 0.20 the amplitude increases with approximately 30% relative to the other cases. An increase in solidity leads to an increase in the forces acting on the net (see Eq. 3 and 4), and thus an increase in dynamic amplitude should be expected. What is interesting to note however, is that the dynamic amplitude of the bottom element force has the opposite development with larger loads for the smaller solidity. The reason for this is that an increase in solidity also increases the damping effect on the net movement, causing the net to move less which again gives smaller element forces in the bottom element.

Case 6. Bottom weight. The main function of the bottom weight in a fish cage is to prevent deformation of the net when exposed to waves and current. For this purpose the weight should be as large as possible, but a large bottom weight also increases the loads on the net as can be seen in Fig. 13. The dynamic amplitudes increases considerably with increasing bottom weight, especially at the bottom element where the dynamic amplitude increases approximately seven times when the bottom weight increases from 10 kg to 40 kg. An increase in bottom weight will thus have a larger impact on the forces on the joint between the net and the bottom weight than on the joint between the net and the floater.

Conclusions

The behaviour of a flexible structure which interacts with a fluid is very complex, and the simple model presented here clearly illustrates this. When flexible structures such as fish cages are located at locations increasingly exposed to waves and
current it becomes important to consider all the different effects of the net behaviour in order to prevent fault and breakdown in the installations. This emphasizes the importance to have reliable numerical tools for predicting net cage behaviour in the design phase of a fish farm.

Acknowledgment

This work was funded by the Norwegian Research Council (NFR) through the research program *3 Dimensional netpen movement and mooring of fishfarms*.

References


**Figure 1.** Overview of the net model.

**Figure 2.** Orientation vector \(\mathbf{n}_o\), element unit normal vector \(\mathbf{n}_{en}\) and angle of attack \(\alpha\).
**Figure 3.** Force - elongation characteristics of a knotless nylon net panel with flag oriented geometry (Tronstad, 2000). The net panel was 45 x 45 [cm], and had 20 meshes in each direction. The mesh side length was 22.5 [mm], and the twine diameter was 1.5 [mm].
Figure 4. (a) Hydrodynamic and structural forces acting on the elements, and (b) element forces distributed to the nodes. $m_n$ is the mass [kg], and $w_n$ is the weight [kg] of element $n$ (weight is the mass subtracted the buoyancy: $w = m - \nabla \rho$). $x_n$ is the position of element $n$. 

(a) 

gravity unit vector $n_g = [0, 0, -1]$
**Figure 5.** The model used in the simulations seen from the side and front when net orientation is 90°. The top and bottom elements and nodes nr. 3, 10 and 21 are used in the subsequent analysis, and are indicated on the figure.
Figure 6. Case 1. Net orientation: Trajectories to three of the node points on the net (node nr. 3, 10 and 21) for five different net orientations relative to the wave and current direction. Settings of the other parameters: top point: follow, wave: 3s/1m, current: 0.5m/s, net solidity: 0.1, bottom weight: 20kg.
Figure 7. Case 2. Top point movement: Element force in the top and bottom element in the net, both when the top point is forced to move with the wave in heave and when the top point is fixed. The surface elevation (wave) is shown at the top. The abscissa value is time normalized with respect to the wave period. Settings of the other parameters: net orientation: 90°, wave: 3s/1m, no current, net solidity: 0.1, bottom weight: 20kg.
Figure 8. Case 3. Wave: Element force in the top and bottom element in the net for three different conditions of incoming waves. Abscissa value as in Fig. 7. Settings of the other parameters: net orientation: 90°, top point: fixed, no current, net solidity: 0.1, bottom weight: 20kg.
Figure 9. Spectral density of the element force time history for $T=4s$ from case 3 (dashed line in Fig. 8).
**Figure 10.** Case 4. Current: Element force in the top element, element force in the bottom element and drag force in the net for three different conditions of current. Drag force is taken to be the horizontal component of the element force in the top element, and is defined to be positive. The surface elevation (wave) is shown at the top. Abscissa value as in Fig. 7. Settings of the other parameters: net orientation: 90°, top point: follow, wave: 3s/1m, net solidity: 0.1, bottom weight: 20kg.
Figure 11. Principal mean net position with current running both against and with the waves.
Figure 12. Case 5. Net solidity: Element force in the top and bottom element in the net for three different conditions of net solidity. The surface elevation (wave) is shown at the top. Abscissa value as in Fig. 7. Settings of the other parameters: net orientation: 90°, top point: follow, wave: 3s/1m, current: 0.5m/s, bottom weight: 20kg.
**Figure 13.** Case 6. Bottom weight: Element force in the top and bottom element in the net for three different conditions of bottom weight. The surface elevation (wave) is shown at the top. Abscissa value as in Fig. 7. Settings of the other parameters: net orientation: 90°, top point: follow, wave: 3s/1m, current: 0.5m/s, net solidity: 0.1.