Open Ocean Aquaculture Engineering II

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ABSTRACT

The University of New Hampshire, Center for Ocean Engineering (UNH/COE) Open Ocean Aquaculture (OOA) engineering efforts continue to be focused on developing engineering design and analysis tools for assessing, evaluating and optimizing engineering systems required for successful open ocean aquaculture. During 2002, this effort was focused on four tasks to continue the understanding of OOA: 1) investigation of commercial size cages, 2) Expansion of the mooring system at the experimental location, 3) feed buoy development, and 4) net panel drag studies to enhance the understanding of this issue. Commercial size cage investigations included numerical and physical modeling of the SADCO-Shelf fish cage, and an initial study of a Sea Station 3000 cage with a tension leg mooring. Analysis of the expansion of the existing mooring was begun to study the effects of having many cages and larger cages at the site. Feed buoy development moved forward with the deployment of a separate independently moored system. The drag studies on net panels provided insight to the increased drag due to biofouling of experimental panels deployed at the offshore site. This paper presents selected results from these four tasks.

I. INTRODUCTION

The need to move the aquaculture industry offshore to more energetic locations is a significant engineering challenge. The goal of the OOA project is to stimulate the development of a commercially viable open ocean aquaculture industry by developing and demonstrating technically appropriate and environmentally sound technologies and culture methods. The University of New Hampshire (UNH) has established a fully permitted demonstration site five miles off the New Hampshire coast (Figure 1) and has made significant advances in engineering and biology for offshore culture. The belief is that if the technologies survive in the challenging North Atlantic then they should be able to survive in numerous, high energy, open ocean locations throughout the world. UNH maintains and operates the site as an open ocean laboratory to test new species, technologies, and to investigate regulatory and environmental issues. This site is used for joint research activities with academia, government and industry. The project consists of seven main components including; 1) site selection and permitting, 2) engineering, 3) biology - finfish and shellfish, 4) environmental monitoring, 5) education and outreach, 6) economics and 7) technology transfer to commercial aquaculture.

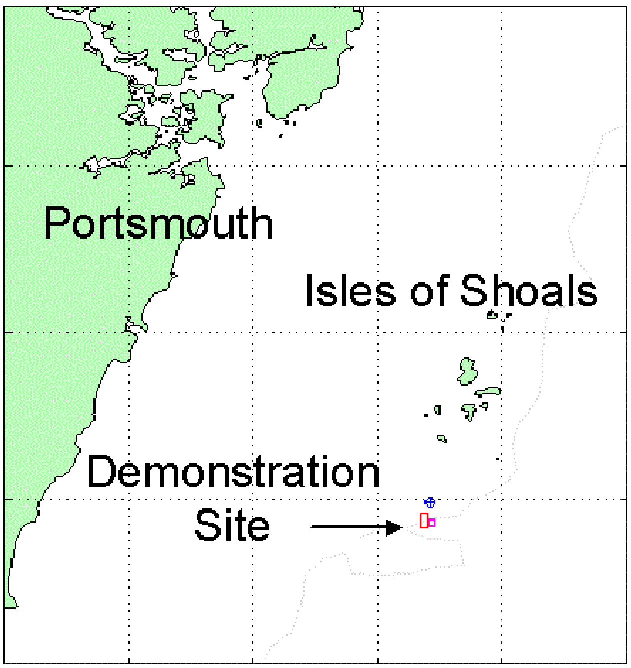

Figure 1. Chart showing location of OOA site off the coast of New Hampshire.

The development of technologies and engineering methods is essential if the United States is to establish an economically viable open ocean aquaculture industry and compete on an international scale. Through the Open Ocean Aquaculture (OOA) demonstration project at the University of New Hampshire (UNH), fish cage and mooring systems have been designed using numerical and physical models, built and deployed at an exposed site south of the Isles of Shoals in the Gulf of Maine (Muller, 1999; Tsukrov et al., 2000; Fredriksson et al., 2000; Baldwin et al., 2000; Irish et al., 2001). The site and equipment is being used as an open ocean laboratory to fully examine the deployed system to understand hydrodynamic properties and the response to oceanic forcing (Irish et al., 2001; Fredriksson et al., 2003a; Fredriksson 2003b). Using knowledge gained from this research, the physical and numerical modeling techniques are evolving to reflect the dominating physical processes (Palczynski, 2000; Fredriksson, 2001; Tsukrov et al., 2003). Even though the techniques and engineering methods are being developed, however, engineering challenges still have to be overcome to develop the technological basis for commercial scale aquaculture.

The goal of the OOA project is to establish a commercial scale facility at the Isles of Shoals site. The engineering component supports this goal by pursuing the following objectives: Investigation of commercial-scale fish cage systems, expansion of the existing mooring grid system at the OOA site, and feed buoy development including design, control/telemetry and modeling.

To successfully accomplish these objectives, the numerical and physical modeling tools and input parameters must continue to be developed as the systems become more complicated. The physical and numerical models need to better represent the nets, and the wave forcing characteristics at the site. Therefore, in addition to the objectives listed above, the following complimentary tasks were initiated: a net panel study to investigate drag and mass characteristics of clean and bio-fouled nets, and a wave measurement buoy validation study. The remainder of this paper describes the progress to date on the stated objectives and tasks.

II. Investigation of Commercial Size Systems

A. SADCO-SHELF:

The analysis of commercial scale fish cage and mooring systems was initiated with the REFA tension leg system as described in Baldwin et al. (2002) and Tsukrov et al. (2003b). Next, the commercially available SADCO Shelf© fish cage and mooring system was investigated for potential open ocean use using numerical and physical models. With these models, shown on Figure 2, tests were conducted in a variety of conditions using both regular and random waves in surface and submerged deployment positions. The cage was subjected to sets of regular waves with periods ranging from 2.4 to 12 seconds, and a random sea typical of coastal New Hampshire with a significant wave height of 3.5 meters. Decew (2002) provides a detailed description of the entire analysis and results.

Assuming a linear system, the motion response of the fish cage in heave, surge and pitch, and the load response of the mooring lines were analyzed to predict the cage dynamics in the open ocean. In general, the surface models predicted a damped system, which is ideal for a fish cage in the open ocean. This reduces the stresses on the cage and mooring system, as well as the fish.

The greatest heave response of the system occurred at the lower wave frequencies, notably at 0.083 Hz. The physical model displayed a high surge response from 0.1 Hz to 0.2 Hz, but the cage retained its shape remarkably well. The orientation of the SADCO tension lines and ballast system kept volumetric stability throughout the applied wave frequencies in both models. The models had minimal pitch response throughout the applied frequencies. The tension in the anchor lines, without a current, is acceptable at 40 kN shown in the numerical model under the design wave with a period of 8 seconds and a height of 9 meters. The surface loads under a current (1 m/s at the surface, linearly reducing to 0.25 m/s at the bottom), as shown in the numerical model, with a tension of 160 kN may push the operational limit of the anchors and mooring lines.

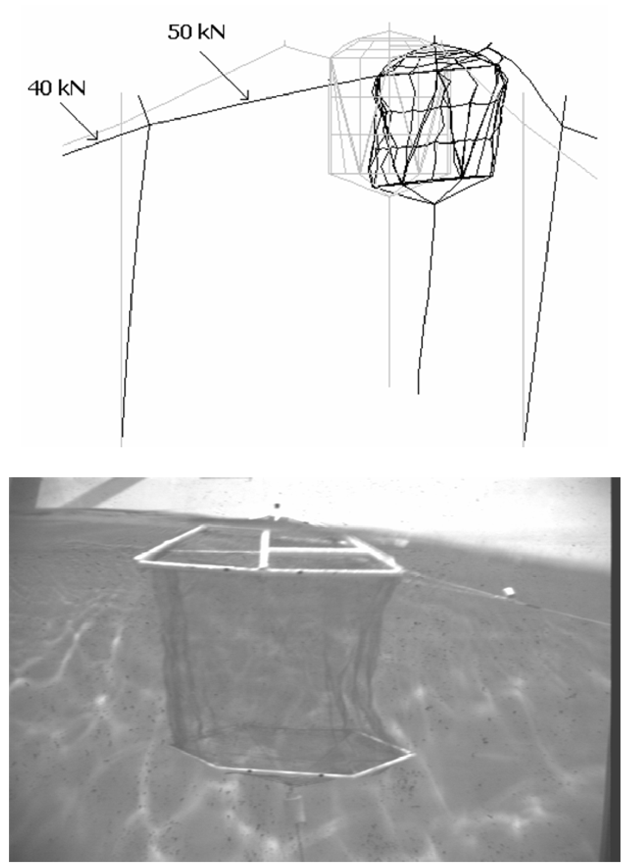

Figure 2: Numerical (top) and physical (bottom) models of the SADCO-Shelf fish cage.

The submerged cage models, on average, displayed 40% to 50% less movement than the surface cage models. This is expected due to less wave energy present at depth. The models predicted an over damped system at depth throughout the wave energy spectrum. The numerical model predictions of tension in the mooring lines also dropped considerably when the cage was submerged, dropping 69% and 75% in the anchor and bridle line load, respectively, under the design wave.

The test results indicate the SADCO system would be able to withstand the normal environmental conditions present in the Gulf of Maine. Under extreme conditions, such as waves similar to the UNH design conditions (consisting of a nominal 9-meter wave, with a period of 8.8 seconds), the cage would have to be submerged due to the large loads present on the mooring system. The tension in the anchor lines needs further investigation to see if the anchors pull out of the sediment and shift the 3 point grid system. This could have profound effects on the dynamics and strength of the mooring system if an anchor is displaced. This cage should be compared to other offshore cages to determine the most economical, robust and reliable system for use in the open ocean.

B: Tension Leg Mooring with SeaStation 3000

Another commercial size fish cage and mooring system considered was an adaptation of the Sea Station 3000 (SS3000) designed by Ocean Spar Technologies (OST) in Bainbridge Washington. The SS3000 was modified to incorporate feeding and harvesting systems. A schematic of a potential configuration is shown on Figure 3.

One mooring system being considered consists of a four-point tension leg grid configuration with compliant members to enable the cage move partly with the seas, but stiff enough to maintain station. This work is building upon past research investigating tension leg moorings described in Fredriksson et al., (1999). In this study, however, the mooring includes a compliant component consisting of a new technology utilizing strong, high stretch hoses. This concept was considered for oceanographic moorings, but has never been incorporated in a fish cage mooring. A preliminary computer model, Figure 2, was constructed of the SS3000 cage with the extended spar feeding mechanism. Simulations indicate that this configuration has promise as a simple, small footprint mooring system, which can withstand the harsh environmental conditions.

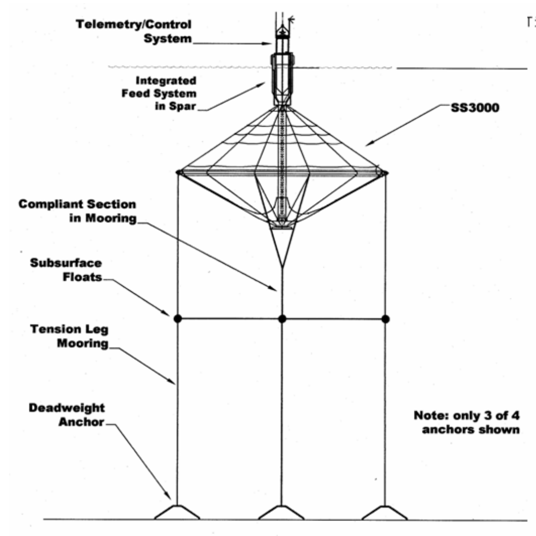

Figure 3: Tension leg 3000 m^3 Sea Station Cage (SS3000) with integrated feed and harvesting (not shown) systems.

III. Expansion of Mooring System Grid

To establish a commercial size facility at the OOA site, the existing independent grid systems must be expanded. Two configurations are being considered: 3-grid and 4-grid mooring systems. This represents an extension of work previously done by Ozbay (1999) and Tsukrov et al. (1999) where 2-grid moorings were investigated. In the last year, however, additional numerical models were built incorporating the new mooring system configurations with models of the existing Sea Station 600 m^3 cages (SS600) and the SS3000 cages. Finite Element Analysis, using the UNH *AquaFE* program, predicted the dynamic response of these new systems under the UNH design conditions. Information on the dynamics, displacements of critical nodes, and stress fluctuations on the critical mooring lines is used to estimate the overall performance of the system and compatibility of the SS600 and SS3000 cages with new mooring designs. In this study the response of the system was investigated in both surface and submerged positions of fish cages.

A: 3-Grid Mooring System Numerical Model

The numerical model of the 3-grid mooring system configuration, Figure 4, was constructed in *AquaFE*. The model incorporated three fish cages including the two SS600s and one SS3000. The mooring system components were chosen to be similar to those presently deployed at the site (see Muller 1999 and Fredriksson 2001 for details). The overall area for this mooring design is approximately 105400 m^2 when projected on the sea bottom.

The system uses 12 anchors attached to the structure, and assumed fixed for the modeling simulations. The anchor chain is modeled as 12 truss elements and the anchor lines as 8 connected truss elements. The direction of the anchor lines is perpendicular to the grid mooring which forms a 19-degree angle with the seafloor. The triple horizontal grid is 37-m. above the bottom and is composed of 3 equivalent (65-m x 65-m) squares that are modeled as 4 truss members for each side of the square. There are 8 buoys attached on the corners of the squares, which causes pretension on the triple squared grid assembly (approximately 5500 N buoyancy force each buoy). The bridles are each modeled using 4 truss elements. The system was modeled in both surface and submerged configurations and the results compared.

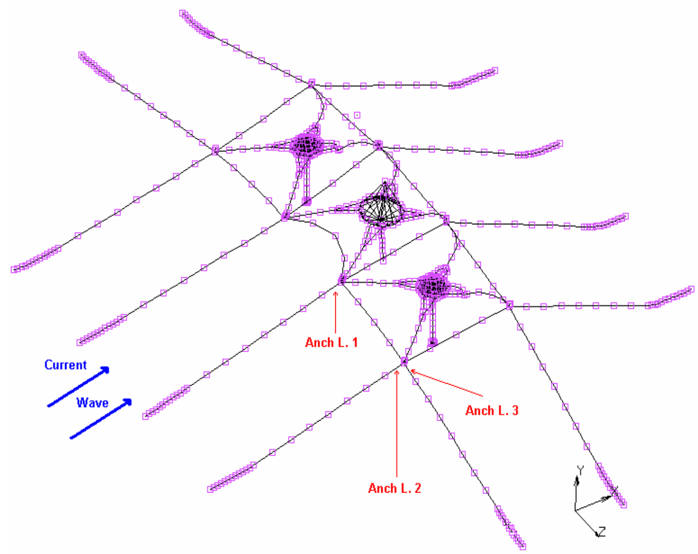

Figure 4: Three-grid mooring system model with two SS600 and one SS3000 fish cages.

B. 4-Grid Mooring System Numerical Model

A second mooring design considered for the demonstration project is a 4-grid system, Figure 5. A numerical model was built using components similar to those presently deployed at the site. This model, however, includes two SS600 and two SS3000 fish cages. The geometry of the mooring system was similar to that of the 3-grid configuration, except with four squares. Simulations were performed in the surface and submerged configurations using the UNH design condition.

It should be noted that this portion of the research is ongoing and therefore the preliminary results are not presented. The model simulations are only one step of the design process that provides an estimation of the dynamic response of the fish cages and mooring line forces. Using these results, each of the mooring system components including lines, anchor and fasteners (i.e. shackles) will be scrutinized for survivability under the design conditions.

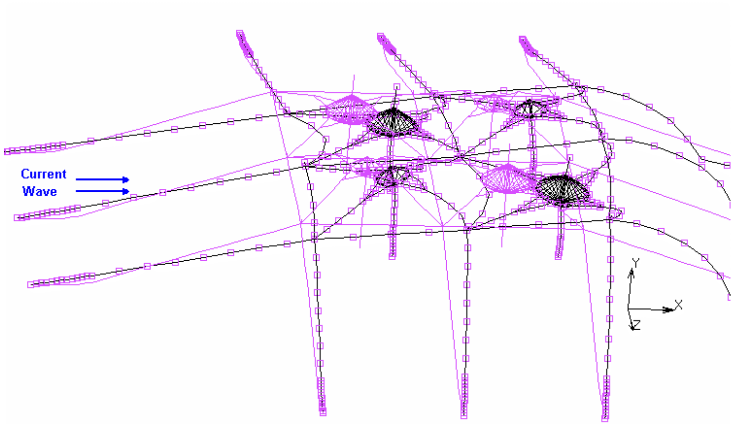

Figure 5: System deformation of the 4-grid mooring with two SS600 and two SS3000 fish cages using the UNH design condition described in Fredriksson et al. (2000).

IV. Feed Buoy Development

Developing automated feeding is required for establishing a commercial size facility at the OOA site. A reliable method of supplying regulated feed to fish in submerged fish cages in the open ocean environment is not commercially available in the United States. Considerable effort to develop a small-scale feed system to reliably supply feed to submerged cages in the harsh marine environment of the Gulf of Maine is ongoing by researchers throughout the OOA project. One of the systems being considered utilizes a surface buoy, moorings attached to the grid system, a feed transfer hose, feed dispensing and telemetry/control systems.

In the fall of 2001, a prototype “feed buoy” was deployed at the OOA site shown in Figure 6. The original feed buoy had a simple feeding mechanism relying upon gravity to carry the feed to the cage though a loose hose at timed intervals. Periodic clogging of the hose and timer malfunctioning were fundamental issues associated with this first generation of feed system, though the survival of the shell and components were promising.

Figure 6: Initial feed buoy deployed at the site.

In the summer of 2002 the buoy was recovered for a general overhaul and reconfiguration with a number of improvements. In the winter of 2002, the second generation feed buoy system was deployed. The buoy was moored with compliant elastic mooring lines, and a taut rubber high-stretch hose, which connects the feed buoy to the submerged fish cage. An additional custom-made flotation ring is included. To reduce feed clogging in the rubber stretch hose, the buoy was moored with elastic tethers to keep the feed hose taut and a new check valve assembly incorporated. The system uses small water pump to pump the feed. A small wind turbine and solar panel are used to generate power for the increased power demands of the pumps and valves. The simple timer was replaced with a more sophisticated control system that can switch the power to the various pumps on a user set schedule, and also monitor the operation of the whole system (charging, power drain on each circuit, battery condition, etc.).

The system controller utilizes a spread spectrum radio to send diagnostic and status information to shore. This link allows for some control of the offshore system from the managers desk. The high-stretch feed hose has integrated conductive wires to send power down to, and receive data back from instrumentation in the fish cage. The first measurements include temperature, salinity along with two video cameras. The video signals are sent to the buoy, digitized then transmitted by wireless Ethernet to shore where the manager can observe the fish during the feeding operation. The integration of a load cell into the feed hose is planned for engineering studies. These data complement the information acquired from the motion packages in the buoy and on the cage spar. All these data are required for understanding the dynamics of the cage and feed buoy, and for optimizing the FEA and the design.

A. Modeling

Computer models of feed buoy system are being developed to assess force and motion dynamics so that components and design can be chosen to withstand the high-energy environment of the demonstration site. The finite element model of feed buoy is presented in Figure 7.

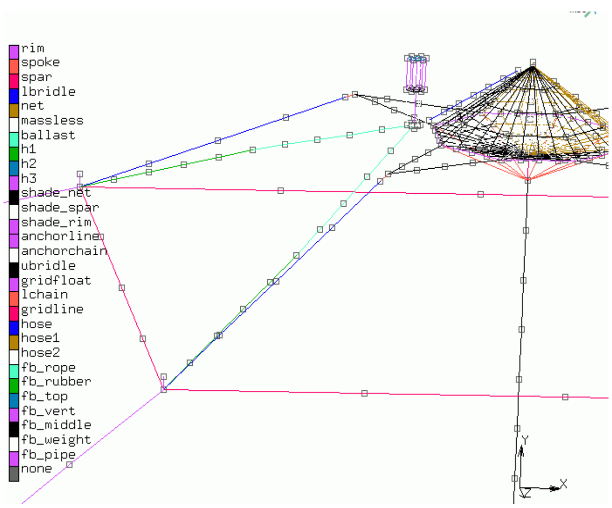

Figure 7: FE model of feed buoy attached to the grid mooring with SS600 cage.

A nonlinear truss element (with piecewise linear elastic properties) was implemented to model feeding hose elastic behavior.

To adequately predict the tensions in the mooring lines, especially under extreme loading conditions, it is very important to accurately model inertia, buoyancy and hydrodynamic forces acting on the feed buoy. The drag force is proportional to projected area, but buoyancy and inertia are proportional to volume of the buoy. Thus set of truss elements can not *exactly* reproduce the forces acting on the feed buoy. Three different models of the feed buoy were used in the computer simulations (1) Model 1 has exact drag, but inertia and buoyancy are underestimated (2) Model 2 has exact inertia and buoyancy, but drag is overestimated (3) Model 3, based on compromise between first two models, has slightly underestimated inertia, buoyancy and slightly overestimated drag.

The dynamic performance of the feed buoy system with various mooring line designs was investigated for both typical and extreme environmental loading conditions. Under typical loading conditions (1.2 m wave and constant current 0.25 m/s) position of feed buoy is very stable and tensions in mooring lines are small (Figure 8).

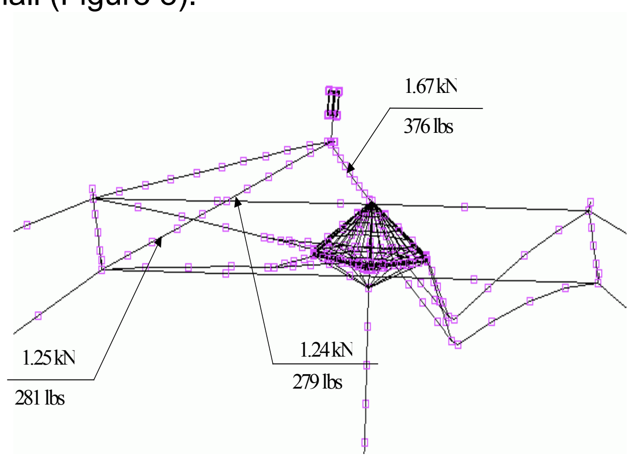

Figure 8: Typical loading conditions. Western wave and current. 6 rubber tethers per leg. Rubber length 11 m.

The design condition consists of a nominal 9-meter wave (with a period of 8.8 seconds) and a current, which is set to change linearly from 1 m/s on the surface to 0.25 m/s near the bottom. The finite element simulations show that this extreme environmental loading results in large deformations and tensions that are higher than maximum working load for rubber tether (170 lb), see Figures 9, 10 and 11, for models 1, 2, and 3 respectively.

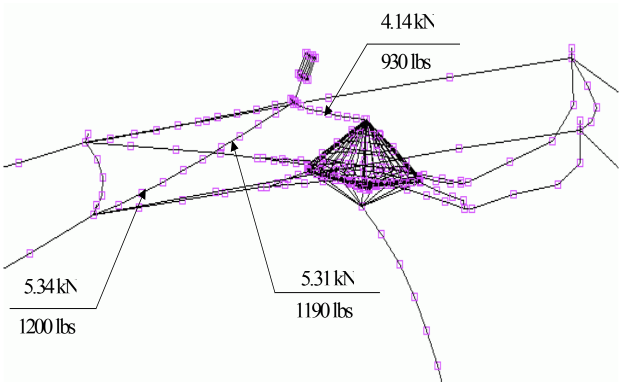

Figure 9: Extreme loading conditions. Western wave and current. 6 rubber tethers per leg. Rubber length 15 m. Model 1 (exact drag, underestimated inertia).

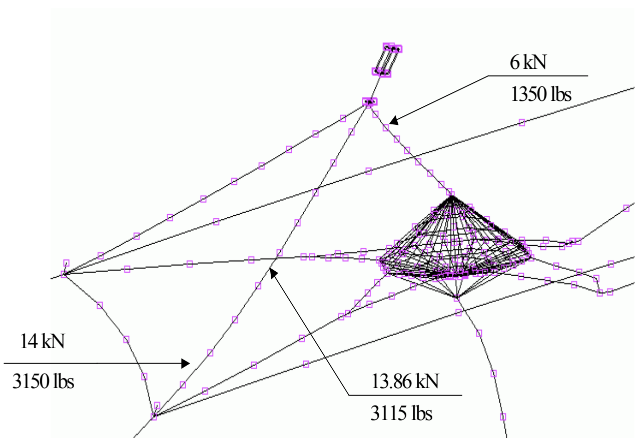

Figure 10: Extreme loading conditions. Western wave and current. 6 rubber tethers per leg. Rubber length 11 m. Model 2 (exact inertia, overestimated drag).

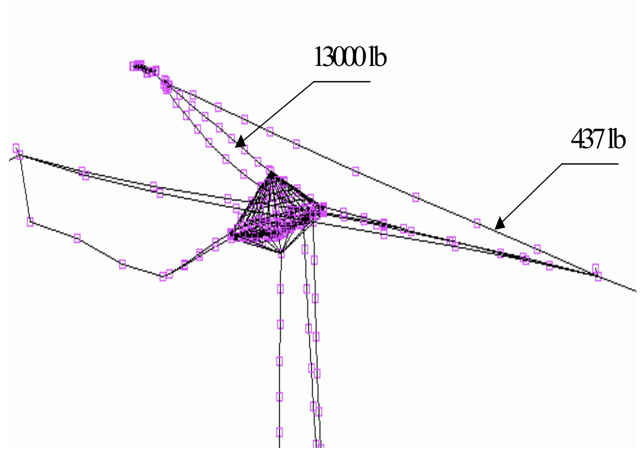

Figure 11: Extreme loading conditions. Northwestern wave and current. 2 rubber tethers per leg. Rubber length 8.5 m. Model 3.

V. Net Drag Study

Research continues to investigate some of the fundamental physical processes that affect the design of open ocean aquaculture systems. The drag due to waves and currents on the net component of a fish cage is one of the primary design concerns, for example, see Palczynski (2000) and Fredriksson et al. (2003c). Measurements were made of steady state drag force acting on one-meter-square net panels, oriented at normal incidence, for tow speeds ranging from ½ to 2 knots. Experiments were done for clean, fish cage netting in the UNH 120 foot long tow tank, while testing of biofouled panels was conducted in the field. Panels consisted of one-inch-square mesh, 1/8-inch-diameter thread netting tightly stretched within a square frame of one inch PVC pipe. The drag force of the frame only was also measured so drag force of just the netting could be inferred. Measurements were made using a 50 lb. capacity Interface Super Mini load cell (model SM-50) connected by thin fish line to a tow bridle arrangement.

Bio-fouled panels were obtained by deploying net panels at the OOA site during the winter of 2001-2002. Drag testing in the field was done using a non-powered catamaran towed alongside a small research vessel as described by Fullerton et al (2002). The panel mounting configuration was exactly the same as that used with the tow carriage in the tank tests.

Results of 134 tow experiments (including duplicates) were processed to yield force as a function of tow speed and drag coefficients. For the one-meter-square net (only), the force at two knots was 42 lbs. The average drag coefficient based on actual net thread projected area was 1.175, while the drag coefficient based on net outline area was 0.279. For netting slightly fouled with small mussels, the drag coefficient based on thread area was 3.236, while drag coefficient based on outline area was 0.754. The corresponding values for netting heavily fouled with algae were 6.764 and 1.576, respectively.

In a complementary effort, a study was initiated to measure the effectiveness of various coatings (provided by E-paint) on reducing drag force due to current on nets subject to bio-fouling. The approach was to measure drag of "clean" panels in the UNH tow tank, deploy the panels at the OOA site, and re-measure drag force as a function of current after recovery. Seven one meter by one meter panels were used including both coated and uncoated nets. The panels were tank tested shortly after delivery to UNH Ocean Engineering near the end of August, 2002. They were deployed at the OOA site on September 20, 2002, recovered on December 18, 2002 and field tested on December 19, 2002.

The tank test results indicated that "clean" drag coefficients (based on thread projected area) are in the vicinity of 1.2. This value is realistic since cylindrical drag coefficients within the test Reynolds number range are about 1.2, and the net panels are effectively made up of superimposed cylinders. The field test data for biofouled netting varied according to coating effectiveness. For the netting with the heaviest growth, the drag coefficient increased by over 900%.

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