Chapter 3
Technological Approaches to Longline- and Cage-Based Aquaculture in Open Ocean Environments

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Abstract As the worldwide exploitation rate of capture fisheries continues, the development of sustainable aquaculture practices is increasing to meet the seafood needs of the growing world population. The demand for aquatic products was historically satisfied firstly by an effort to expand wild catch and secondly by increasing land-based and near-shore aquaculture. However, stagnation in wild catch as well as environmental and societal challenges of land-based and near-shore aquaculture have greatly promoted efforts to development farming offshore technologies for harsh, high energetic environments. This contribution thus highlights recent technological approaches based on three sample sites which reach out from sheltered near-shore aquaculture sites to sites with harsh wave/current conditions. It compares and evaluates existing technological approaches based on a broad literature review; on this basis, we then strongly advocate for presently available aquaculture technologies to merge with future offshore structures and platforms and to unveil its added value through synergetic multi-use concepts. The first example

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describes the recent development of longline farming in offshore waters of New Zealand. New Zealand has designated over 10,000 ha of permitted open ocean water space for shellfish farming. The farms range from 8 to 20 km out to sea and a depth of 35–80 m of water. Research has been ongoing for the last 10 years and the first commercial efforts are now developing in the Bay of Plenty. New methods are being developed which should increase efficiency and reduce maintenance with a particular focus on Greenshell mussel (*Perna canaliculus*) and the Pacific Oyster (*Crassostrea gigas*), Flat Oyster (*Tiostrea chilensis*) and various seaweeds. The second case study involves a long-term, open ocean aquaculture (OOA) research project conducted by the University of New Hampshire. During the course of approximately 10 years, the technological aspects of OOA farming were conducted with submersible cages and longlines, surface feeding systems and real time environmental telemetry. The grow-out potential of multiple marine species such as cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), halibut (*Hippoglossus hippoglossus*), blue mussel (*Mytilus edulis*), sea scallop (*Placopecten magellanicus*) and steelhead trout (*Oncorhynchus mykiss*) were investigated at a site 12 km from shore. The last study presents a multi-use aspect of aquaculture for an open ocean site with fish cages attached to existing offshore wind energy foundations. Technological components such as mounting forces and scour tendencies of two different cage structures (cylindrical and spherical) were investigated by means of hydraulic scale modeling. The cages were pre-designed on the basis of linear theory and existing standards and subsequently exposed to some realistic offshore wave conditions. The wind farm "Veja Mate" in German waters with 80 planned 5 MW turbines anchored to the ground by tripiles is taken as the basis for the tested wave conditions. Based on findings stemming from the three example approaches conclusions are drawn and future research demand is reported.

3.1 Introduction

As the worldwide exploitation rate of capture fisheries continues, the development of sustainable aquaculture practices is increasing to meet the seafood needs of the growing world population. The demand for aquatic products was historically satisfied firstly by an effort to expand wild catch and secondly by increasing land-based and near-shore aquaculture. However, stagnation in wild catch as well as environmental and societal challenges of land-based and near-shore aquaculture have greatly promoted efforts to development farming offshore technologies for harsh, high energetic environments. As a consequence, ocean domestication is of key importance to maintain the ocean as a sustainable source of food, both economically and ecologically (Marra 2005).

While the annual growth rate of aquaculture production has been 6.3%, total aquaculture production grew from 34.6 million tons in 2001 to 59.9 million tons in 2010; thus it depicts the second important sector to supply the continued global demand for marine proteins (FAO 2012). In 2010, world marine farming production was estimated at 36.1 million tons with a value of US$37.9 billion (FAO 2012). Nearly all ocean farming is conducted inshore, in contrast to offshore aquaculture that is still in its infancy. Offshore aquaculture may be defined as taking place in areas of the open ocean exposed to significant wind and wave action, and where there is a requirement for equipment and servicing vessels to survive and operate in severe sea conditions from time to time (Drumm 2010).

There is an obvious, demand-driven need to develop offshore aquaculture throughout the world. However, one of the most difficult obstacles to overcome is finding locations for new aquaculture farms. Because of the difficulties associated with inshore locations, it is assumed that most new aquaculture activities will be developed offshore in the Exclusive Economic Zone (3–200 miles) where there are fewer conflicts with existing user groups, and less risk of pollution. The high energy (winds and waves) of such exposed locations, however, present significant technical challenges in the design, testing and construction of aquaculture systems that are capable of surviving in these areas. In addition to these technical challenges, there are many biological, regulatory, social and economic problems to be solved.

Despite, drivers at local and global levels provide impetus for aquaculture to move to these unprotected waters of the open sea. There are issues of competition for space with other users, problems with water quality, and oftentimes there is a negative public perception of aquaculture’s environmental and aesthetic impacts (Kapetsky et al. 2013). Some of these conflicting issues are also common to the offshore wind energy and oil industry. The oil/gas industry has a long history of installed facilities in offshore locations. The recent pressure to reduce carbon dioxide emissions has additionally leveraged the worldwide planning and installation of offshore wind energy converters. Countries bordering the North and Baltic Sea with limited accessibility of inland building sites such as Denmark, Great Britain or Germany started exploring offshore wind energy feasibility in the end of the eighties (Hau and von Renouard 2006). High energy cost and natural disasters facilitated this development. It is thus natural to assess if foundation structures (piles, tripods, jackets) of existing or licensed wind energy sites could be co-used for additional economic activities such as offshore aquaculture.

Aquaculture migration towards offshore sites has undergone substantial progress in the last two decades. This progress was leveraged by advances in numerical and physical modelling of various fish cages or long line arrangements as well as by technological developments and prototype sites. In order to design an open ocean aquaculture test site near the south of the Isles of Shoals, New Hampshire a numerical model was used by Tsukrov et al. (2000) to optimize the structure. Finite element analysis was applied to study the performance of surface and submerged constructions and a simplified formulation for the simulation of the nets is presented. An improved formulation was presented by Tsukrov et al. (2003) offering a consistent net element which is generally capable to model fluid action and net inertia of fishing nets and allows to simulate environmental loadings originating from currents, waves or other mechanical impacts. Motivated by the impact of storm-waves to aquaculture facilities, a lump-mass method was used to study to the effects of currents to net-cage systems and good agreement was found between the numerical results and prior experimental findings (Huang et al. 2006).

Experimental studies most often provide the basis for numerical modelling attempts, help calibrating numerical models and verify achieved simulation results. Experimental research offers down-scaled, controllable and repeatable conditions for reliable analysis which becomes increasingly important as study sites move from more sheltered near-coast regions to high-energetic offshore sites. The effects of current-only conditions on down-weighed flexible circular nets were investigated in greater detail experimentally by Lader and Enerhaug (2005). They emphasized that forces on and deformations of flexible nets are mutually highly dependent on each other. This in particular applies to aquaculture sites residing in the open ocean with harsh environments. The suitability of a modified gravity-type fish cage was similarly investigated by experimental and numerical means under exposed environmental conditions with regular waves (DeCew et al. 2005). These controlled wave conditions allowed for the derivation of motion response in heave, surge and pitch as well as load response in the anchor and bridle lines. The findings were then extended to the irregular regime by the application a stochastic approach. Based on a combination of numerical and experimental approaches Huang et al. (2008) conjectures aquaculture activities should not be situated waters with current velocities above 1 m/s unless volume-reducing effects can be safely restricted by technological means. At the same time it is recommended to carefully consider the combined effects of currents and obliged waves before facilities are installed at new sites.

Although the tendency to aquaculture site located further off the shore is well traceable in literature there are generally much fewer sources which explicitly focus on the combination of different aquaculture applications at one location or even inclusion of non-aquaculture elements such as support structures from other industries in the open ocean. Buck and Buchholz (2005) discussed the co-use of existing or planned offshore structures for the growth of *Laminaria saccharina* by comparing drag forces measured in a current flume with those resulting from conditions in the North Sea. The authors also reported on the development of a devices to culture macroalgae in a range of offshore conditions (Buck and Buchholz 2004). Based on the analysis of the current development inside the continental shelf around the world Lacroix and Pioch (2011) plead innovative efforts to move towards eco-engineered structures such as artificial fishing reefs or the incorporation of secondary purposes within wind farms. The mutual benefits of wave energy converter foundations as artificial reefs were examined for a building site about 100 km north of Gothenburg at the Swedish coast (Langhamer and Wilhelmsson 2009). It was found that basically the amount of fish and crab on the ground of the foundations was considerably increase whereas the abundance of fish in the water column above was not substantially altered. Another example of the multi-use idea is the development of artificial reefs which oftentimes serve not only the purpose to provide valuable habitat to marine species but also serve as one additional form of coastal protection (Liu and Su 2013).

This contribution presents recent technological advances and innovative approaches towards aquaculture production in harsher oceanic conditions on the basis of three case studies involving the idea of multi-use. The recent advancements of tools and methods to study the response of aquaculture technology to environmental loading such as winds, waves, currents and other mechanical impacts describe above serve as the basis for the presented studies. Technological challenges and existing obstacles due to the high-energetic environment are discussed at the end. Within the first two case studies, currently available potential and challenges of aquaculture is discussed in light of its applicability towards harsher environments and high-energy impacts from winds and waves. Then, we extend our analysis and the conclusions drawn from those first two case studies and present a unique third case study. Therein, existing aquaculture cage technology is thoroughly tested as it is innovatively attached to a commonly used offshore wind energy converter foundation, called a tripile foundation. For the first time, such a multi-use concept was tested under laboratory conditions with valuable conclusions and inter-comparisons between existing and anticipated offshore technologies being reported in the discussion and conclusion chapter.

3.2 Case Study on Long Lines

3.2.1 Mussel Farming Development in NZ

Mussels (the Greenshell™ mussel, *Perna canaliculus*) are the main shellfish in both mass and value to be farmed in New Zealand. They have been farmed in sheltered and semi-sheltered areas since the industry started in 1979. The current production has fluctuated between 86,000 and 101,000 ton per annum between 2011 and 2014. Mussels are farmed using the New Zealand longline system, the general structure of which is discussed below. There are variations to this theme depending on location and farmer preference.

In 2003 consents for the offshore aquaculture space were lodged and the process of obtaining this space started. There were numerous reasons for the departure from the sheltered waters including user conflict and a desire to increase farm size. The proposed farms were in waters ranging from 6 to 20 km off the coast in water depths ranging from 35 to 80 m.

In 2005, the first experimental ropes were installed into the open ocean waters of Hawkes Bay. The first open ocean structure was based on the traditional mussel backbone but it was influenced by the systems used in the Coromandel in the North Eastern corner of New Zealand North Island. The Coromandel generally has higher energy than that of other culture sites such as the Marlborough Sounds.

A traditional inshore New Zealand mussel longline consists of: a mooring; chain; warp; bridal; backbone; bridal; warp; chain and mooring (Fig. 3.1). The early moorings were Danforth type anchors. These were overtaken in preference by

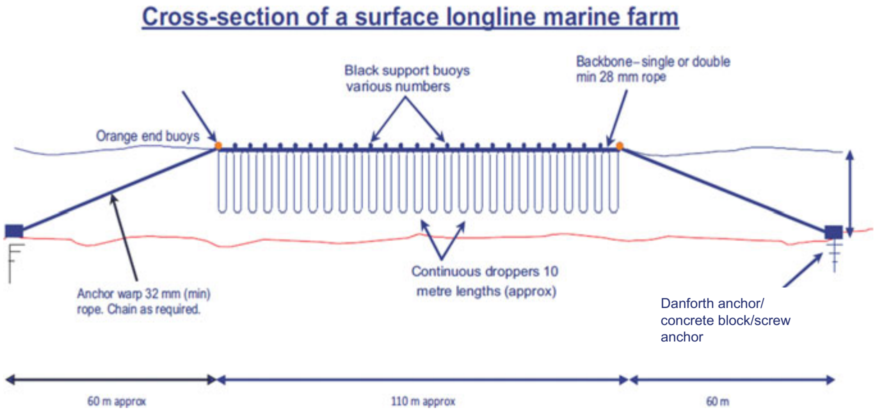

Fig. 3.1 Cross section of a New Zealand surface longline *Credit* New Zealand Marine Farmers Association

concrete shaped moorings of up to 10 metric tons (22,200 lb.) in mass. Where possible concrete mooring are being superseded by screw anchors when new ropes are being installed and the substrate is suitable.

The chain is a heavy duty chain of 6 m (20 ft.) to 15 m (50 ft.) in length. A synthetic rope of 27 mm (>1 in.) to 36 mm (1½ in.) called a warp is attached to the chain and rises to the bridal. The warp is generally three times the depth of the water. The bridal splits into two, each split attaching to a header rope on the opposite edges of the float line, respectively. This section of the mussel longline holding the buoys or floats is called the backbone. Since this backbone has a header rope on each side of the float to support the production line it is referred to as a "double backbone". The backbone extends to the opposite bridal and so on. The buoys are 1.3 m across (∼4 ft. 3 in.) and spaced appropriately to support the mass of growing mussels on the backbone. Typically the backbone ranges from 100 m (328 ft.) to 200 m (656 ft.) long. A mussel longline (production rope) is hung from the backbone. It is attached on one side, descends down to 10 or 15 m, loops up to the opposite side of the backbone and crosses the gap between the buoys and the descends down again. Each loop being approximately 50 cm (20 in.) to 70 cm (28 in.) apart along the backbone. In this way, between 3000 m (9842 ft.) and 4000 m (13,123 ft.) of mussel long line is hung from a 100 m backbone.

The longline hanging from the backbone can produce between 6.5 kg (14 lb. 5 oz.) to 13 kg (28 lb. 10 oz.) per meter (or 4 lb. 12 oz. per ft. to 9 lb. 8 oz. per ft.) depending on site and situation. The time period to produce this would range from 12 to 20 months, again depending on site and location.

As the industry changed from inshore to more exposed sites the backbones were cut down to a single header rope (single backbone) i.e. there is no bridal and the warp joined directly to the backbone (Fig. 3.2) and the production longline is draped in loops along the single header rope or backbone. The backbone is submerged and has approximately 66% of the floatation attached directly to it.

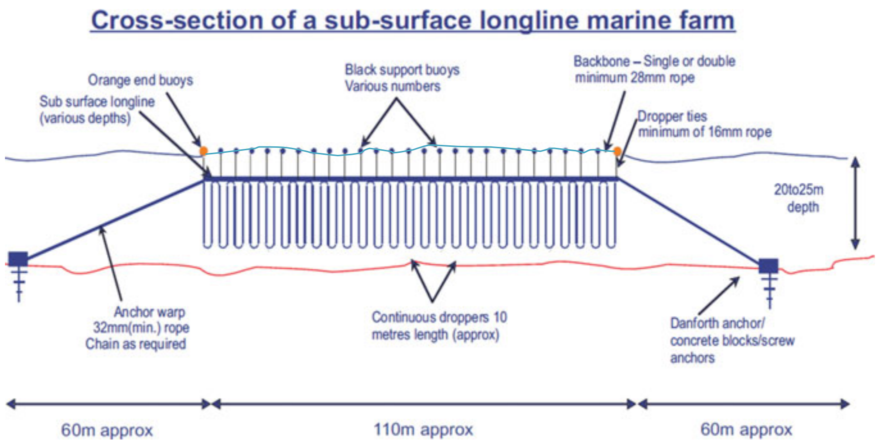

Fig. 3.2 Cross section of a New Zealand subsurface longline. *Note* More recent systems have more floats on the submerged part of the longline *Credit* New Zealand Marine Farmers Association

Additional floatation is positioned on the surface with strops extending from the surface floats to the backbone. The length of the strop dictates the depth of the backbone.

The surface floats will provide 30–40% of the floatation and also give some indication of the load the backbone is bearing and when additional floatation will be required. The backbone is installed loose enough so that a hook can be lowered from a vessel to snag the backbone and the resultant apex of the snagged backbone brought to the surface. The spacing between the droppers may be increased when compared to the inshore systems and may be as much as 1 m (3 ft. 3 in.) apart. By submerging the ropes, this system provides some protection from the wave energy experienced in open ocean situations, however, the surface floats still transfer energy to the backbone which can result in production losses and increased maintenance. In addition, there is an issue arising from the additional requirement in flotation as a result of mussel growth, i.e. once the farm has a large number of backbones on it the management of floatation will increase significantly.

There is no doubt that new systems will be developed in the future. The next generation system that is currently being developed and tested is the "Set and Forget" (S&F) system. This system, developed by the Cawthron Institute (www.cawthron.org.nz) in conjunction with an open ocean farming operation and Government funding (MBIE and Kiwinet), is a fully submersible double backbone system which will be deployed and recovered from the surface.

The S&F system (Fig. 3.3) has a similar configuration to the surface double backbone but where the bridal meets the backbone, there is a mooring directly below it (screw anchor). There are additional intermediate anchors spaced every 35 m along the backbone. These intermediate moorings are threaded through a mechanism in the S&F buoy. There are also single S&F attachment mechanisms on

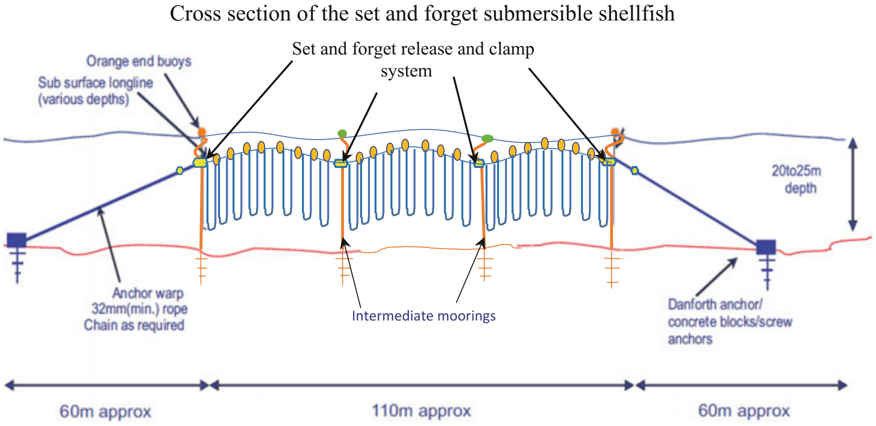

Fig. 3.3 Set and Forget system—next generation submersible backbone under testing (www.cawthron.org.nz)

each warp with a surface float. The idea is to fully seed the longline on the backbone. The backbone is then floated with sufficient buoys to support the intended harvest mass. Once seeded the backbone is pushed below the surface to the desired depth and the S&F mechanism engaged. The mechanisms on the warps are tightened to ensure the backbone does not collapse towards the center. The mussels can then be left until they are due to be harvested. No intermediate floatation is required. At harvest the mechanisms are released using a surface driven unit (physically not electronically) and the backbone rises to the surface to be harvested.

3.2.2 Oyster Farming in the Open Ocean

Oysters have also been tested on the open ocean sites. Although there are several methods used, inshore only bags have been tested in the offshore situation. Pacific oysters (*Crassostrea gigas*) have been held in purses or oyster bags (Fig. 3.4). The bags are configured one below the other in a “ladder” configuration. There are 20 bags in a ladder spaced approximately 50 cm (20 in.) apart with 50–100 oysters in each bag depending on bag size and oyster’s size. Some work is required in the design of the bags to reduce the maintenance of the present ladder system. Baffles have been introduced into the bags/purses to avoid the oysters being clumped into one corner of the unit. Oysters have to be at a minimum depth below the surface to avoid being “rumbled” by the wave energy which restricts shell growth. The level of floatation has to be managed to reduce excessive energy transfer to the culture units. Oysters have shown growth rates comparable with inshore waters in North Island. The Flat oyster *Tiostrea chilensis* will be tested in the same ladder system in

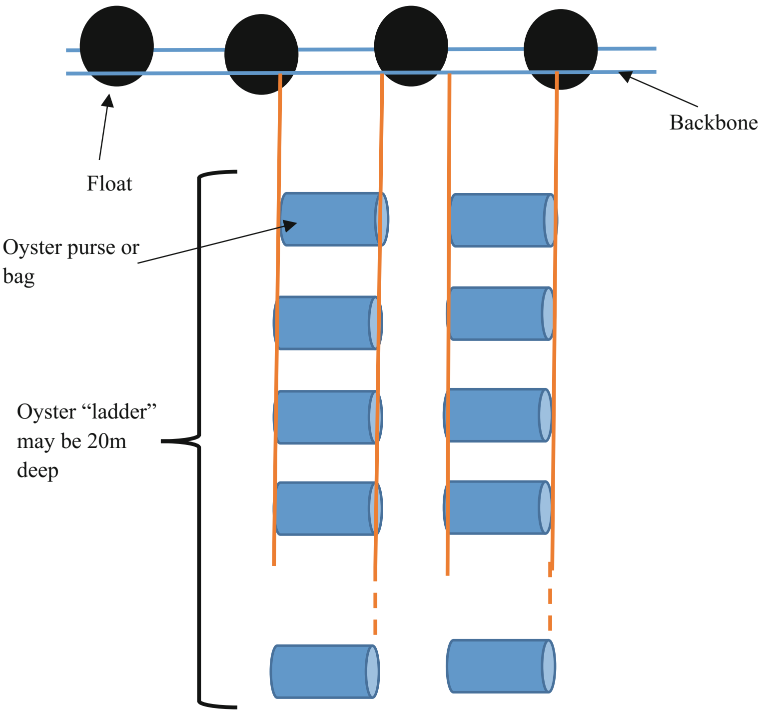

Fig. 3.4 Oyster purses being hung in a ladder configuration on the backbone

the near future on the open ocean farm. Early indicators are that flat oysters will grow in this system if they are away from direct wave energy.

3.3 Case Study on Submerged Aquaculture

3.3.1 Open Ocean Aquaculture in New Hampshire, USA

The University of New Hampshire (UNH) established the Open Ocean Aquaculture (OOA) research farm in 1999 (http://ooa.unh.edu/). The overall goal of the project was to stimulate the further development of commercial offshore aquaculture in New England. Also important was to work closely with commercial fishermen, coastal communities, private industry, and fellow marine research scientists to develop technologies for the aquaculture of native, cold-water finfish and shellfish species in exposed oceanic environments. The site was located 12 km offshore and in 52 m water depth, away from traditional fishing activities, recreational vessels and commercial traffic.

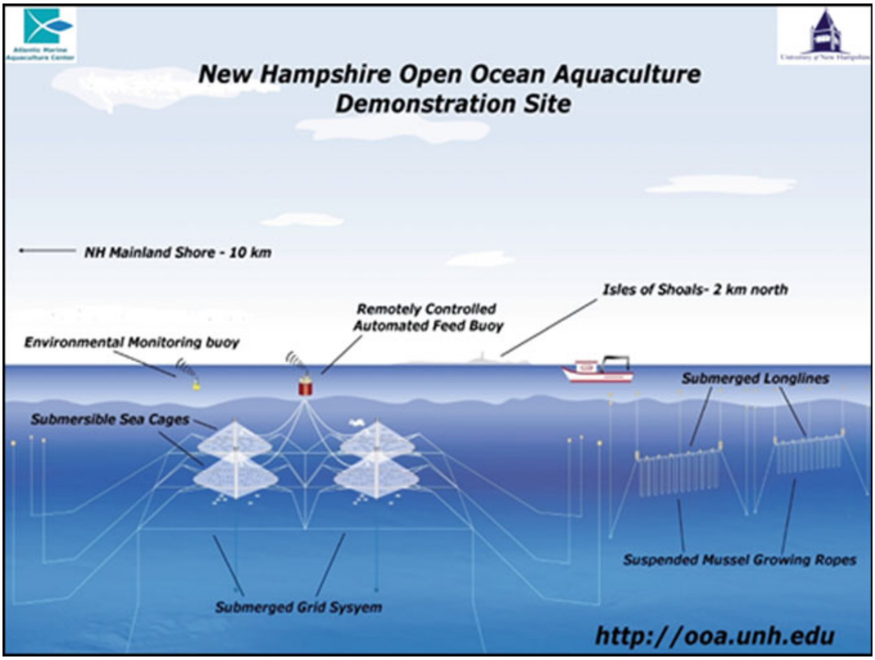

Fig. 3.5 Schematic of the University of New Hampshire Open Ocean Aquaculture site located 12 km offshore New Hampshire, USA

Prior to aquaculture systems going offshore, they were analyzed through numerical and physical scale modeling at the Jere Chase Ocean Engineering lab on campus. These tools help identify strengths and weaknesses of components, simulate failure scenarios and help determine safety factors before they deployed and field tested (Fredriksson et al. 2004; Swift et al. 1998; Tsukrov et al. 2000). The backbone of the OOA research farm was a 12 Ha, submerged grid for holding surface and sub-surface systems (Fig. 3.5). The four bay mooring had a scope of 3:1 and was held in place by 12, 1 ton embedment anchors (Fig. 3.6). The mooring complex was made from 5 cm dia. Polysteel lines that were tensioned and held in place by 1.43 m composite subsurface buoys in the corners and center of the grid (DeCew et al. 2010a, 2012; Fredriksson et al. 2004). The robust grid provided the necessary infrastructure to evaluate submersible cage systems (Chambers et al. 2011; DeCew et al. 2010b). One such system extensively tested was the Sea Station^{TM} 600 and 3000 m^3 cages (Fig. 3.7a). Using a central spar with pennant weight, the cage could be submerged to a prescribed depth or lifted by compressed air to the surface. It utilized a Spectra net that shackled to the top and bottom of the central galvanized spar and used a middle ring that gave its bi-conical shape. Also evaluated offshore in the grid was a 600 m^3 geodesic Aquapod^{TM} made with triangle panels and hard wire (Fig. 3.7b). This system was neutrally buoyant and be could set at various depths based upon the mooring configuration. Ocean Farm Technologies produces the

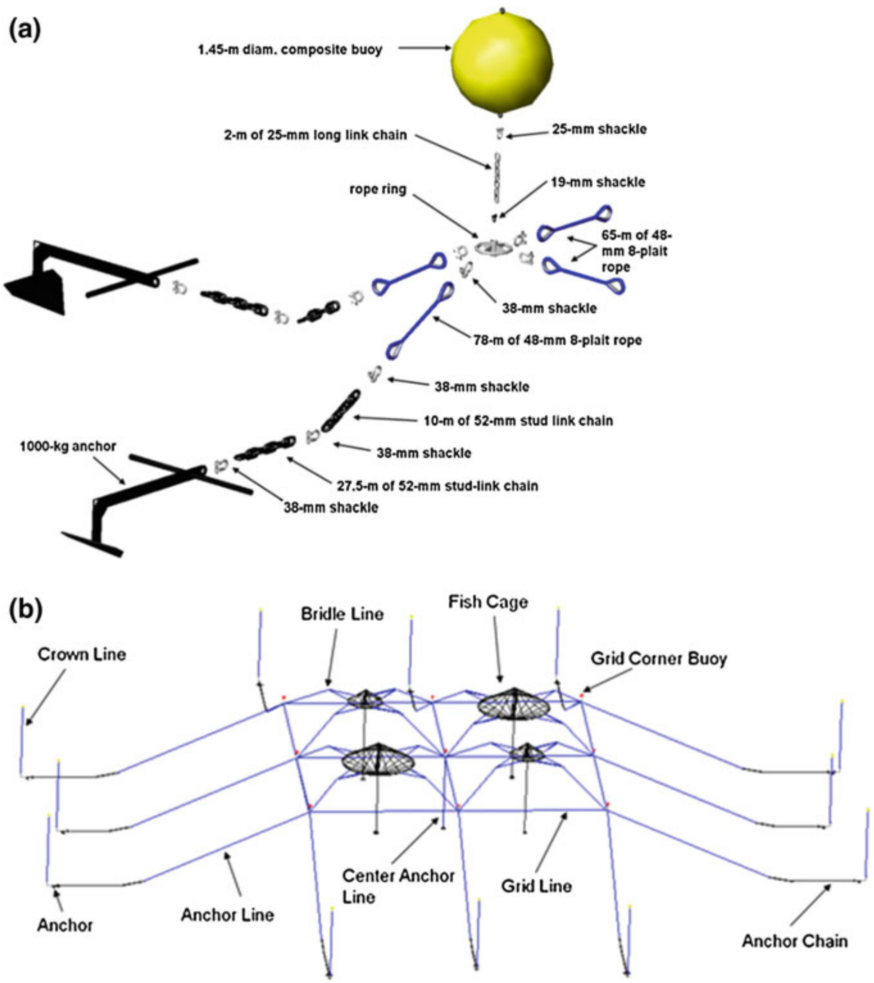

Fig. 3.6 Submerged grid mooring (**a**) and corner grid assembly (**b**). The side anchor assembly was similar except for the use of only one anchor leg and a 0.95 m steel float

Aquapod™ and since their initial sea trial in NH, have made many advances to their containment system. The American Soybean Association International Marketing (ASAIM) came forth with the Ocean Cage Aquaculture Technology (OCAT) system (Fig. 3.7c). The 100 m^3 cage OCAT (2 m × 4.5 m × 7 m) was constructed of HDPE pipe with galvanized steel fittings. Chain ballast hangs below the lower cage rim providing a restoring force. The net chamber is formed by attaching net panels to the cage framework. Engineers at UNH designed and evaluated components in the cage frame to make it a submersible system (DeCew et al. 2010b). Information gathered at the UNH OOA site helped these three companies improve their containment systems and increase global sales.

(a) Sea Station™ **(b) Aquapod™**

(c) OCAT

Fig. 3.7 Submersible cage systems (**a–c**) evaluated offshore New Hampshire. They include the Sea Station™, the Aquapod™ and the Ocean Cage Aquaculture Technology (OCAT)

Marine finfish species including summer flounder (*Paralichthys dentate*), cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), halibut (*Hippoglossus hippoglossus*), and steelhead trout (*Oncorhynchus mykiss*) were cultured and harvested from the research farm (Chambers and Howell 2006; Chambers et al. 2007; Howell and Chambers 2005; Rillahan et al. 2009, 2011). Hatchery production for cod, haddock and halibut was challenging with growout time in the sea cages ranging from 2.5 years (cod) to 3.5 years (halibut). Initially, fish were fed daily from a vessel through a feed hose that attached to the top of from the surface. An onboard water pump was used to mix food pellet and seawater in a funnel chamber before it was pushed down into a cage 12 m below. Autonomous feeders were not yet developed for the open ocean. Hence the design course that UNH Engineers embarked on to create three new generations of feeding systems (Rice et al. 2003). Prototype buoys evolved and scaling up to a final 20 ton version (Fullerton et al. 2004; Turmelle et al. 2006) that was fabricated by AEG in New Brunswick, CA (Fig. 3.8). The buoy hull was 8.6 × 6.9 m and had a draft of 3 m fully loaded with feed and fuel. To keep the buoy upright, 22,135 kg of concrete was poured into bottom. Fish food was pneumatically blown from a vessel into one of the four,

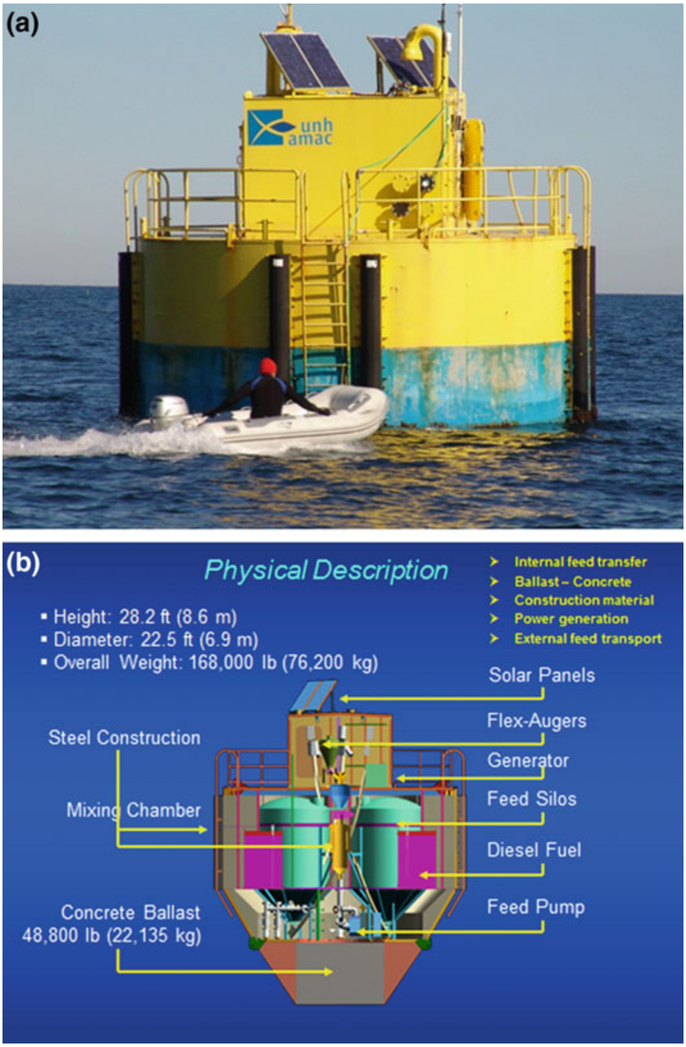

Fig. 3.8 Remote 20 ton feed buoy used to hydraulically feed four submersible sea cages up to 300 m away

5 ton silos. The house on top contained the majority of the electrical equipment as well as the generator for powering computers, pumps, valves, and augers used in daily feeding. During feed time, a flex auger would deliver feed pellets (5 mm) from the bottom of a silo to a mixing chamber in the top house. Feed rates were based upon fish species, size, biomass and temperature. In the mixing chamber, seawater was added before the feed was pumped hydraulically to individual cages. The buoy was moored adjacent to the cage grid by three, 750 ton Jeyco anchors. Feed distribution lines (4), consisting of 10 cm dia. High Density Polyethylene

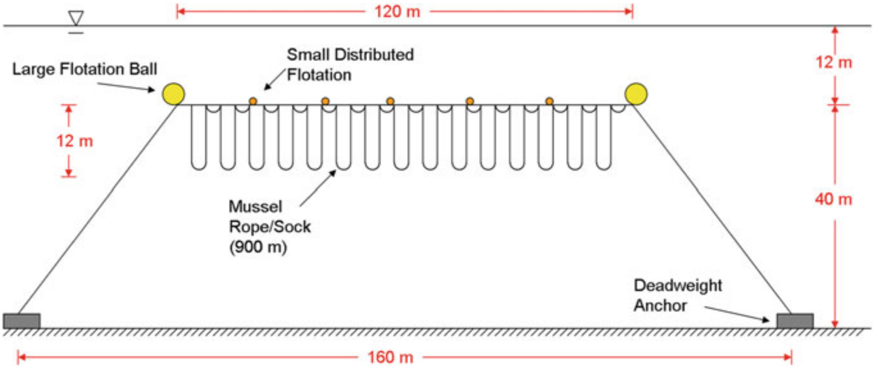

Fig. 3.9 Typical long-lines configuration for mussel grow-out. Dimensions are those used at the UNH OOA site and are representative

pipe, bolted to a manifold on the bottom of the buoy. They extended from the buoy to the submerged grid approximately 200 m away. Individual feed lines then integrated into the grid system and on to the top of each cage. Video cameras inside the cages were cabled through the feed lines back to the buoy.

Submerged shellfish longlines were designed and deployed next to the mooring grid (Figs. 3.5 and 3.9). Each 40 m long line was moored between two, 3000 kg dead weights (granite blocks) and set 12 m below surface to escape wave energies and predators (diving ducks). The backbone had surface lines so that it could be hauled up for seeding, cleaning or harvest. Approximately 900 m of mussel rope or sock could be deployed/line, able to produce between 8000 and 12,000 kg of blue mussel (*Edulis Mytilus*) per year (Langan and Horton 2003). The sea scallop (*Placopecten magellanicus*) was investigated on the submerged lines in stacked pearl nets. Problems with bio-fouling and stress from cleaning lead to low survival rates of this species.

Information important to scientists and farm managers was environmental conditions at the OOA site. This data was collected and streamed live from a single point, wave rider monitoring buoy (Irish et al. 2004, 2011). Figure 3.10 illustrates the instrumentation used at varying depths on the elastic buoy mooring. Oceanic parameters measured were wave height, current speed and direction (surface), temperature, salinity, oxygen, turbidity and fluorescence (at 1, 25 and 50 m depths).

Operations offshore were difficult to perform under winter conditions, heavy seas and with SCUBA divers. During the winter months, cages could not be accessed for several weeks at time thus minimizing days at sea for maintenance. Submerged cage systems were preferred in the North Atlantic to protect cage infrastructure and livestock. During Northeast storms, seas >10 m were recorded with currents speeds reaching 0.55 m/s. Underwater video cameras inside the cages provided insight to the fish health and feeding. This information was transmitted real time from the cages to the feed buoy and then back to shore through cellular modem.

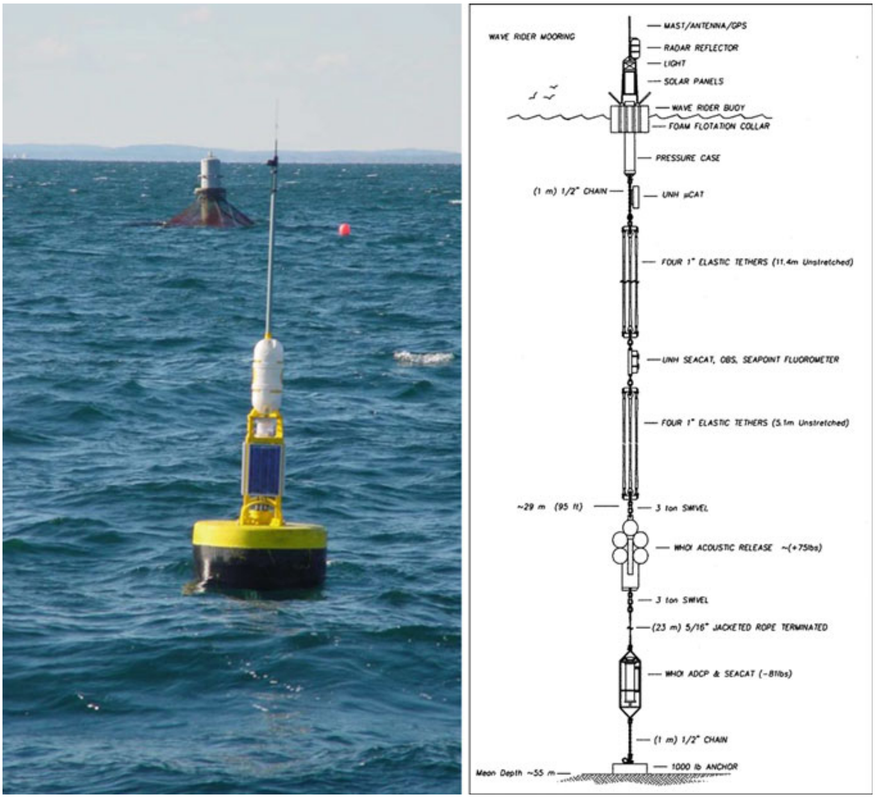

Fig. 3.10 Environmental monitoring buoy moored at the Open Ocean Aquaculture site. Oceanographic parameters measured included wave height, current speed and direction, temperature, salinity, oxygen, turbidity and fluorescence

Although the project succeeded in generating significant amounts of data and new information, the high maintenance costs, exposed nature of the site, and slow growth of marine fish species (cod, haddock and halibut) created operational and economic challenges.

3.4 Case Study on Multi-use on Open Ocean Environment

3.4.1 Methodology

This third case study picks up from the two previous case studies and details how the existing aquaculture technologies might be effectively utilized in a multi-use arrangement. In here, the multi-use of offshore wind energy and open ocean aquaculture is investigated experimentally. The location of interest for this feasibility study resides in the German bight at Veja Mate, which is reportedly 114 km off the shore in the North Sea. The reported results purely base on an experimental feasibility study since the stakeholder conflicts and the financial demand for in situ testing would have been too extreme at the point of development. The case study aimed to shed light on the general behavior of two different fish cage geometries being mounted to a tripile foundation for a 5 MW offshore wind energy converter (OWEC) at different submergence levels. An aspect of the analysis comprises the change of wave induced particle velocity and its distribution around the support structure due to the two fish cages. A second focus has been laid on the forces exposed to the tripile as a result of the additional fish cage bearing by means of force measurements under monochromatic waves. Thirdly the additional effects to potential scour around the tripile are also investigated in order to substantiate earlier findings (Goseberg et al. 2012).

The mechanical system of the fish cage and the OWEC-structure is investigated under regular wave attack with respect to (a) the deviations in the velocity field resulting from the fish cage underneath the OWEC, (b) the additional forces introduced by the fish cage and (c) the potential for scour evolution at the sea bottom of the OWEC location. Therefore a 110 m long and 2.2 m wide wave flume at the Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Hannover, Germany is applied. The experiments are scaled at Froude similitude at a length scale of 1:40. The water depth at the wave maker (piston type) equals 1.0 m, yet to investigate scour evolution at the OWEC-structure a 0.25 m deep sand pit (fine sands of $d_{50} = 0.148$ mm) is installed at a distance of 42 m of the wave maker. At the end of the wave flume a gravel slope acts as passive wave absorption. An overview of the wave flume, its installations and a schematic of the mechanic system under investigation is given in Fig. 3.11. The two fish cage models were made of solid brass. Variations with three different surface properties (net solidity) were accomplished under the attack of monochromatic waves.

Based on a potential building site in the German bight at Veja Mate, a frequent (mean) and an extreme wave with a 50-yearly reoccurrence interval have been chosen. In model scale investigated wave heights are $H = 0.04$ m with $T = 0.95$ s for the frequent case and $H = 0.28$ m with $T = 2.2$ s for the extreme wave condition respectively. Surface elevations are measured with capacity-type wave gauges at various positions. Deviations in the velocity field around the structure and the fish cage are recorded by either ADV probe inside the fish cage or by stereo PIV measurements around the fish cage. Wave-induced forces at the constructional conjunctions between fish cage and tripile legs are taken by force transducers measuring normal forces. Force measurements are designed to consequently separate horizontal and vertical forces. Therefore all conjunctions between the fish cage and the tripile legs are designed as pendulum rods whereas the vertical forces are assumed to be gathered by a single tension rod connected to the upper tripile intersection. Compression-tension type force transducers (HBM GmbH) with a capacity of 500 N and an accuracy of 2% of its capacity were used. Scour depth evolution was manually measured with sediment gauges of 2 mm PVC sticks which were observed by underwater cameras (Abus GmbH). This optical method

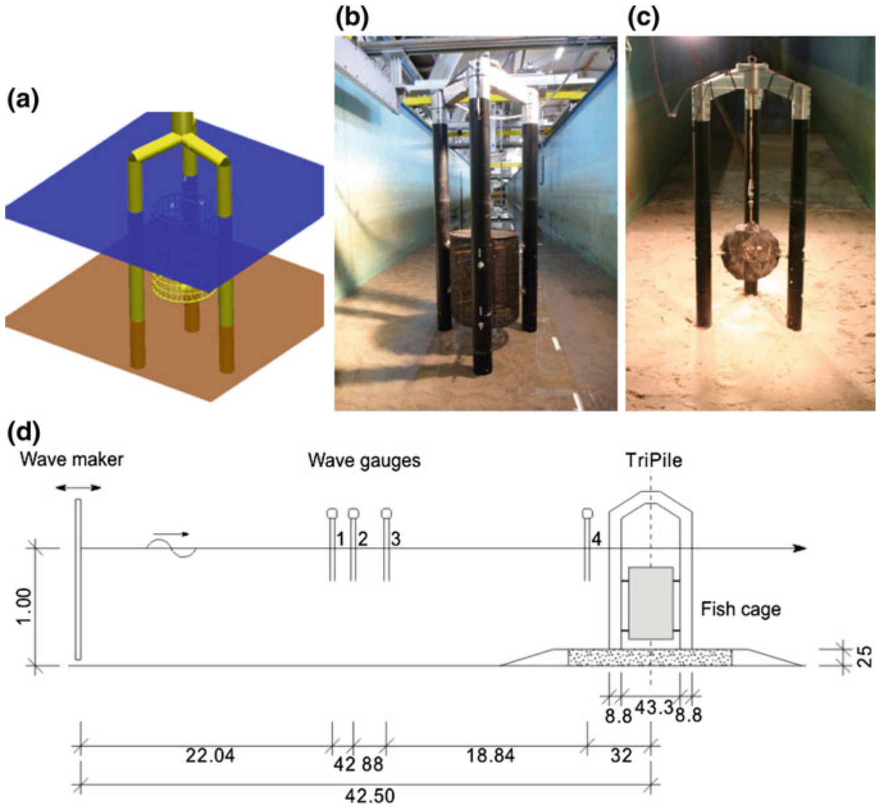

Fig. 3.11 **a** Schematic of the OWEC and cage arrangement. **b** Tripile model with cylindrical fish cage, **c** tripile model with spherical fish cage, and **d** longitudinal section of the wave flume with wave maker, position of wave gauges, sand pit and tripile model

where the difference between the initial and actual bed level is read from a centimeter scale on the PVC sticks based on the camera recordings gave reasonable accuracy (±0.5 cm).

3.4.2 Velocity, Force and Scour Regimes

Velocity measurements are accomplished to investigate the velocity regime in the vicinity of the OWEC-structure and its deviations by means of a fish cage installed inside the tripile legs. Foremostly, this part of the experimental program was intended to learn how velocities range inside the fish cage under wave attack in order to allow marine biologists to evaluate if fish production is feasible at all and how strong velocities influence the natural behavior of potential marine species

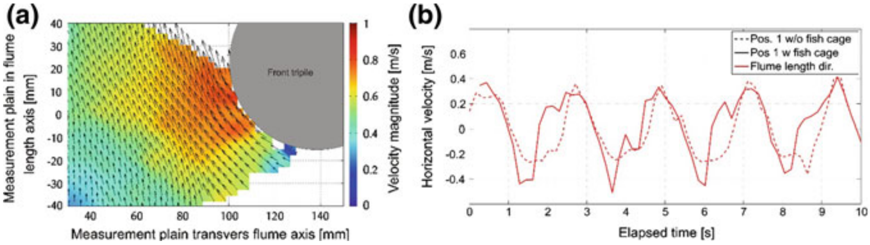

Fig. 3.12 **a** Example vector field of horizontal velocities near the front tripile for extreme wave conditions, upper measurement plain during wave crest propagation along the tripile. **b** Horizontal velocity from PIV-measurements comparing setup with and without fish cages assembled. All velocities reported are in laboratory scale. For prototype conditions multiply by $\sqrt{40}$

inside the enclosure. By means of the particle image velocimetry (PIV) technique (Raffel et al. 1998; Sveen and Cowen 2004) measurements of the velocity field very near to the tripile structure are feasible. Figure 3.12a shows an example of a velocity vector field during a propagation of a wave crest modeling extreme conditions for the cylindrical fish cage design.

Furthermore, the PIV-measurements which are recorded in stereo mode also allow for the extraction of 3D time series of velocities at a discrete position. For the evaluation of additional direct wave forces to the tripile legs the knowledge of velocity distribution is needed. Figure 3.12b hence shows the time series of horizontal velocities taken from PIV-measurements directly in front of the wave facing tripile leg at the height of the fish cage cover. Though maximum positive velocities are not significantly altered, it is obvious that negative velocities during wave trough are increased. Additionally it is apparent that phase duration of positive velocities is extended. With respect to fish cultivated in such a high energy environment a result could be that potential candidates have to be able to withstand such velocity magnitudes unharmed. Besides horizontal velocity components, vertical velocities are similar to their horizontal counterparts increased during the wave trough phase of wave passage. ADV-measurements inside the cylindrical fish cage reveal more moderate velocity changes which could be contributed to the damping effect of the modeled net material. While horizontal velocity deviations between experiments with and without fish cages are not so pronounced, it is apparent that vertical fluctuations are in a range of approx. 0.2 m/s (laboratory scale). This fact could especially influence health and behavior of flatfish which is one of the investigated candidates for the fish cages.

Force transducers in case of the cylindrical fish cage were arranged in two height levels. Force transducers FT_4 to FT_6 were mounted in the upper measurement plain connecting to the tripiles whereas the remainders (FT_1 to FT_3) were measuring forces near the bottom of the fish cages. Vertical forces were monitored with a single vertically arranged force transducer at the top cover of the cylinder. Compression forces were defined positive while tension forces were negative. Force transducers were pre-stressed and then zeroed before each experimental test for

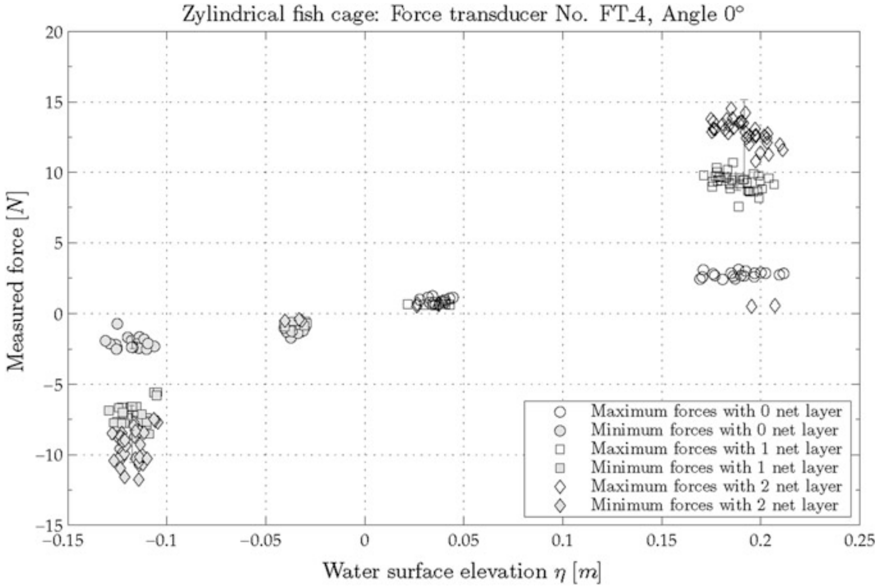

Fig. 3.13 Correlation of maximum wave heights and measured forces for cylindrical fish cages for force transducer FT_4 with respect to the number of net layers

stability reasons. Similarly, the spherical fish cage had three force transducers connecting from the equator of the sphere towards the tripiles plus a vertical force transducer to bear the vertical forces. Highest tension forces appear at the wave-facing tripile leg during the passage of the wave crest. In parallel, these forces initiated by the wave at the front of the cylinder are also measured at the backward force transducers but with opposite sign and vectorially separated.

In order to analyze the correlation between the wave heights and the caused reaction forces a zero-crossing method has been applied to the water surface elevation measurement which was located besides the wave-facing front tripile of the OWEC. Thereafter the maximum values of the surface elevation and the forces have been collected. Experimentally, three different flow resistances are considered. First, the fish cage is tested only with its support structure. One and two layers of net material are fixed to the fish cage in subsequent tests. Figure 3.13 shows an example of the correlation of maximum wave heights and the respective maximum force measured with respect to the number of net layers. In general it is apparent that the additional forces exerted to the tripile structure increase with increasing wave height. Though, the correlation is not linear but growth exponentially. Due to the limited number of wave heights analyzed so far it is yet not feasible to present valid regression functions. The influence of the flow resistance variation is though clearly obvious. While the increase of net layers from zero to one results in an increase of forces of more than 100%, the further increase towards two layers of net material only results in further loading of approx. 40%. The variation of let layer numbers is yet important to investigate how loadings develop under the additional resistance due to marine fouling. Up-scaled overall forces that have to be absorbed by the tripile structure are at least for stormy conditions in the mega newton range and deemed clearly design relevant for the OWEC structure. For the chosen cases, the connecting joints between the investigated fish cage variations are arranged so that bending moments are also induced. In upcoming studies it is thus recommended to lower the connecting joints further down to the sea bottom in order to greatly reduce the effects that aquaculture applications connected to the OWEC would have.

In literature a number of theoretical approaches exist to deduce the maximum scour depths at piles (Melville and Coleman 2000; Sumer and Fredsøe 2002) which nowadays depict an important piece of information for the safety assessment of OWEC. In case of complex marine constructions involving multi-use of an OWEC with multiple, complex-shaped constructional members, the analytical approaches are not easily applicable. Hence an optical method is applied which consists of sediment gauges and image capturing. A manual post-processing routine is chosen to estimate the local sea bed evolution. The local water depth of the modeled OWEC structure and the chosen monochromatic waves limit the scour tendency. Scour evolution is yet possible under the assumption that swell generated in a far field arrives at the location of interest. Therefore additional experiments with an elongated wave period of $T = 3.0$ s are conducted. In this case scour around the tripile legs can be observed clearly. Under the assumed boundary condition relative scour depth of $S/D = 0.54$ is determined at the front leg of the tripile whereas relative scour depth of $S/D = 0.36$ is found below the tower of the OWEC for a setup without a fish cage. Slightly different results are obtained under the presence of fish cages mounted to the OWEC. Relative scour depth of $S/D = 0.48$ (front leg) and $S/D = 0.25$ (central below tower of OWEC) are found. This reduction of scour observed underneath the main tower of the OWEC below the tower can be explained by a reduction of wave-induced flow velocities and shear stresses in this area.

3.5 Discussion and Conclusions

In the following, not only are conclusions drawn from the single case studies but it is highlighted how open ocean aquaculture might benefit from its transition towards a multi-use concept. Direct benefits such as cost reductions through multiple usage of anchor constructions as well as indirect ones like shared usage of supply vessels or personnel indicate that time has come to move aquaculture industry further offshore. Ongoing initiatives such as the European framework funded projects MERMAID, H2OCEAN, and TROPOS are a vital indication of the present demand for research and development in this area.

Open ocean shellfish farming is at a pivotal point at this time. Technology has reached a point where economically viable commercial production is a real prospect. Once production becomes more routine and operating under standard procedures, it is believed that companies will direct greater focus towards improving efficiency in a similar way the inshore longline system developed in New Zealand in the 80s and 90s. In further support of the open ocean mussel farm mentioned in the case study, mussel spat is being caught in commercial numbers as far as 12 km off the coast and may be accessible even further out to sea. This means the whole production chain can be handled on the same farm. It is estimated that this particular farm will deploy 350–400 km of mussel production rope per annum within the next 3–4 years. Once this farm has shown itself to be technically and economically viable, other farm owners have indicated that they will start production. The potential will then be enormous.

There are some considerations regarding production and seasonality that must be taken into account. It has been found that mussels inshore have a longer and more varied condition window than mussels grown offshore (Heasman, unpublished), i.e. shellfish conditioning at the open ocean site is more uniform across the growing area and is shorter in duration. This is an advantage in terms of processing however the shorter window leads to production peaks and troughs. For example, an offshore farm may be capable of producing 30,000 ton of mussels but if they all have to be harvested in a 6–12 week period it will require a large number of vessels and processing capability for that period. These units will sit idle or at low usage for the remainder of the year. For this reason it is important to have multiple species in production simultaneously, unless a species that can be harvested year round is utilized.

Despite the findings in New Hampshire, other open ocean locations and technologies may be more suitable for offshore farming. An example of this is Ocean Blue located 11 km offshore Panama. Here they are raising Cobia (*Rachycentron canadum*), a fast growing warm water species, in 6000 m^3 Sea Station™ cages. Last year they produced 400 MT with an expected 1200 MT by 2014. Currently they feed via day boats through pneumatic blowers into each cage. Commercial feed barges (http://www.akvagroup.com/products/cage-farming-aquaculture/feed-barges/ac-450-panorama) are available however they cannot withstand seas over 4. 5 m. These barges are common in protected water ways in Norway, Chile and Canada. Certainly if aquaculture is to move further from shore, remote feeding systems will need to be improved to withstand seas >10 m. Also important will be real time monitoring of fish behavior and environmental parameters inside and outside the cages. In this, farmers can best manage animal welfare to optimize growth and condition.

Ocean farming will slowly creep offshore as new, economical and robust technologies develop. Farms of the future must be turnkey allowing for remote operations such as feeding, environmental monitoring, fish health and harvesting of product. These platforms could ultimately produce their own energy through wave, wind and tidal turbine technologies. Ultimately, farming centers should be located close to large coastal populations to reduce the carbon footprint from exporting overseas.

For the combination of aquaculture fish cages and OWEC structures, the up-scaled experimental particle velocities at the highest position of the investigated fish cages are in the range of 1.3 m/s under prototype condition for the maximum wave height (storm conditions). This range of velocities is potentially harmful to species candidates to be grown in the North Sea and might negatively affect survival rates and thus reduce economic feasibility of multi-use approaches. Alternatively, the investigated cage systems could be modified in height (decreased) and lowered further towards the sea bottom in order to circumvent the critical particle velocities induced by storm waves. However, volume reduction of the actual fish cages also minimizes the economic potential of the fish cages as the amount of fish is decreased.

This alternative design has similar potential to reduce overall forces at the contact points with the OWEC structure. In addition, as forces grow with the degree of marine growth, net materials with growth retarding characteristics in combination with optimized maintenance cycles might decrease overall forces as well. However, the greatest challenge for further testing in prototype conditions are still the restraints from owners or designers of offshore wind energy parks which reject any additional (and yet untested) loading stemming from secondary purposes for safety reasons. Unless legitimate doubts and technological uncertainties are alleviated through further scientific effort, it seems to date still challenging to expect marine multi-use applications in the near future.

In conclusion, based on differently far developed examples it has been demonstrated that open ocean aquaculture has reasonable potential for future growth and prosperity. In future, multi-use is not only a feasible add-on to farming in open ocean conditions whenever technological or logistical challenges are resolved thoroughly but it might depict the key innovation towards economically feasible offshore farming in high energy environments. For example, it might be beneficial for the aquaculture ventures to rely on pre-existing fixed structures such as piers, foundations amongst others to attach feeding storage, supply equipment or instruments. Rather than constructing and installation of dead weight anchors in rough environments, pre-existing infrastructure is seen advantageous to the installation of various forms of aquaculture technology including fish cages, mussel ropes or net pens. In turn, infrastructure owners would be able to generate additional income through leasing out their property to aquaculture.

However, some technological or logistical challenges which have been described can only be addressed efficiently with the help of stakeholder dialog and proper incorporation of end-users or operators. A chain of development steps from the very beginning of a business idea to the final operation of this business incorporates preliminary design, feasibility studies which involves various modelling steps, a design phase to plan for a prototype development, and eventually an operational farm or multi-use deployment which has undergone further optimization steps to yield its full effectiveness under a wide range of external influences. A number of approaches to tackle those steps of the development cycle have thus been highlighted in this paper aiming to help additional projects to be launched in the future.

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